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EL NINO AND LA NINA EVENTS
AND NORTH ATLANTIC TROPICAL CYCLONES

by

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The largest differences occurred in the middle (July-September) and late (September—November) portions of the TC season. Throughout almost all of the season, there were more TC formations during LN events than during EN events, especially in the tropical North Atlantic (about 10-20°N). However, in the late season, there were more formations during EN events in the subtropical North Atlantic (about 20-30°N). The formation site differences appear to have been mainly the result of lower vertical shear in the tropics during LN events, and lower vertical shear in the subtropics during EN events. The vertical shear differences in the tropical North Atlantic were mainly the result of anomalies in upper tropospheric heights and the tropical easterly jet associated with variations of the Asian summer monsoon. The vertical shear differences over the subtropical North Atlantic were mainly the result of an extratropical anomalous wave train extending from the western North Pacific to the North Atlantic.

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EL NINO AND LA NINA EVENTS AND NORTH ATLANTIC TROPICAL CYCLONES

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LIST OF ACRONYMS

CDC	Climate Diagnostic Center
COADS	Comprehensive Ocean-Atmosphere Data Set
CPC	Climate Prediction Center
EN	El Niño
ENSO	El Niño Southern Oscillation
hPa	Hecta-Pascals
LN	La Niña
MEI	Multivariate ENSO Index
NATL	North Atlantic
NCEP	National Center for Environmental Prediction
NHC	National Hurricane Center
NOI	Northern Oscillation Index
NPNANA	North Pacific-North American-North Atlantic
OLR	Outgoing Longwave Radiation
SLP	Sea Level Pressure
SO	Southern Oscillation
SOI	Southern Oscillation Index
SLPA	Sea Level Pressure Anomaly
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
TC	Tropical Cyclone
TEJ	Tropical Easterly Jet
Z	Height

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I would like to thank Professor Tom Murphree for his insight, wisdom, patience and encouragement, LT Bruce Ford for all that he left behind, and Pat Harr for his ninth-inning save. I would also like to thank my family and friends who helped encourage me through this process. And I would like to give all credit for this paper to my Guiding Light.

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I. INTRODUCTION

A. BACKGROUND

Accurate predictions of local and regional weather rely heavily on an understanding of the large scale background environment. In dealing with changes in the environment, one must consider both temporal and spatial changes. Temporal variations range from diurnal to seasonal and longer changes. Familiar spatial variations include ocean-continent differences, and the differences between the tropics and extratropics. Predictions of the environment suffer when the behavior of the background environment is different than its average and expected behavior.

Examples of large-scale deviations from average environmental conditions include El Niño (EN) and La Niña (LN) events. These interannual events occur in the tropical Pacific and Indian Ocean regions, last approximately one year, and occur about every two to seven years. On a human time scale, EN and LN events produce environmental changes that are second only to seasonal changes in their scope and magnitude. The perturbations induced by EN and LN are associated with fires, floods, droughts, diseases, and national emergencies around the world. Because these events usually only occur every few years, and each event is unique in space and time, it is difficult to predict the occurrence, intensity, and impacts of EN and LN events.

Tropical cyclone (TC) activity in the North Atlantic (NATL) region (e.g., hurricanes) can be remarkably different during EN events than during LN events

(Gray 1984, Goldenberg and Shapiro 1996, Lander and Guard 1999). Variations in TC activity can have major social and environmental impacts. The ability to predict TC formation, intensity, tracks, and duration are of paramount importance, especially considering the large number of people who live along the Gulf of Mexico, and western North Atlantic Ocean. The purpose of this study is to clarify what impacts EN and LN have on NATL TCs, and to identify the mechanisms by which these impacts occur. We hope that by improving our understanding of the impacts of EN and LN events on TCs, we can contribute to an improved use of forecasting resources, improved warnings, and a decrease in the loss of life and property.

B. EN AND LN IMPACTS ON GLOBAL CIRCULATION

In the 1920s and 1930s, Sir Gilbert Walker investigated the connections between global-scale variations in surface pressure. He identified three large-scale pressure oscillations, including the global-scale Southern Oscillation (SO) (Walker 1924). Walker and Bliss (1932) identified significant correlations between the SO and atmospheric conditions around the world (e.g., sea level pressure in the southeastern United States, precipitation in Hawaii, temperature in western Canada). These findings helped pioneer the study of interactions over large distances, some of which are now called teleconnections.

Bjerknes (1969) identified a link between the SO and fluctuations in the eastern equatorial Pacific sea surface temperatures (SST). He described a pattern of anomalously warm SSTs, weak trade winds, and high convection in the eastern and central equatorial Pacific, and anomalously weak convection and

cool SSTs in the western equatorial Pacific. The occurrence of these anomalies in the equatorial region was described as an El Niño event (Bjerknes 1966, 1969). The interannual variations of these anomalies, along with the corresponding variations of sea level pressure anomalies in the South Pacific, have been termed the El Niño Southern - Oscillation (ENSO), a coupled ocean-atmosphere phenomenon. Through his studies of teleconnections, Bjerknes also found that anomalous air-sea interaction in the tropical Pacific could cause anomalous energy exchanges between the tropics and extratropics, which, in turn, lead to changes in global circulation patterns (Bjerknes 1966, 1969, 1972). Several studies (e.g., Bradley et al. 1987) noted that during some non-EN years, opposite anomalies occurred (e.g., unusually strong trade winds along with cooler SSTs in the eastern and central equatorial Pacific). This near-opposite phenomenon has been termed La Niña (LN). Major features of SO, EN, and LN were summarized by Philander (1990).

Modeling studies have shown that convective heating anomalies that occur throughout the Pacific during EN and LN produce tropical and extratropical atmospheric circulation anomalies. Matsuno (1966) and Gill (1980) modeled the tropical response to these heating anomalies and found the forcing can produce an equatorial Rossby-Kelvin wave response, with corresponding responses in the equatorial heating, mass, and circulation fields. Hoskins and Karoly (1981) and others have shown through modeling studies that the Rossby portion of this response may extend into the extratropics, thus producing global atmospheric responses to EN and LN events.

A number of observational studies have described the characteristic extratropical anomalies that occur during EN and LN events (e.g., Horel and Wallace 1981, Murphree and Reynolds 1995, Ford 2000). These characteristic extratropical anomalies describe the teleconnection patterns associated with EN and LN events. The strong resemblance between the modeled wave train responses (Matsuno 1966, Gill 1980, Hoskins and Karoly 1981) and many observed teleconnection patterns indicates that teleconnections are a result of anomalous Rossby wave trains that are triggered by the anomalous atmospheric heating in the tropical Pacific during EN and LN events.

C. TELECONNECTIONS FROM EAST ASIA

Short term and small scale convective heating anomalies in the East Asian-western North Pacific region have been shown to generate anomalous extratropical wave trains that extend from East Asia across the North Pacific-North American-North Atlantic (NPNANA) region. Nitta (1987) linked anomalous upper-tropospheric heights over Japan during the summer to intraseasonal and seasonal anomalies in western Pacific SSTs and convection. He found that anomalously strong convection and high SSTs near the Philippines were associated with unusually high middle to upper tropospheric heights over Japan, and vice versa. This study also found that the high heights over Japan were associated with a wave train that followed a gentle zonal arch from East Asia over the North Pacific. The trigger mechanism for this wave train seemed to be the anomalous convection and SSTs in the western Pacific.

Observational and modeling studies have also found similar responses to tropical cyclone activity in the western North Pacific. (Woll 1993, Springer 1994, Jakus 1995, and Malsick 1995) These studies concluded that interactions between convective disturbances in the tropical and subtropical western Pacific could generate anomalous wave trains that extend into the North Atlantic. These wave trains link convective activity in the western North Pacific and the East Asian monsoon region to the NPNANA region. Ford (2000) suggested that through such links, convective disturbances in the western tropical Pacific and East Asia could alter TC activity in the North Atlantic (Fig. 1).

D. PRIOR STUDIES ON NORTH ATLANTIC TC ACTIVITY AND EN AND LN EVENTS

The effects of EN and LN events on NATL TC activity have been extensively studied. Gray (1984) pioneered this work with a study of correlations between NATL TC activity and ENB events. Since then, numerous studies have been conducted in order to identify in what ways NATL TC activity is altered, what environmental changes in the NATL may explain those alterations, and, to a lesser extent, what mechanisms link the EN and LN events in the tropical Pacific to TC activity in the NATL.

1. Data and Methods Used in Prior Studies

A number of different data sets and methods have been used in these studies. Gray (1984) used 15 strong and moderate EN events that had occurred through the early 1980s. Of these 15 events, only four occurred when extensive observations of TC activity were available from meteorological satellites (after the mid-1970s). Gray contrasted TC activity during the 15 EN events with TC activity

during all other events, including LN events in with periods in periods in which neither an EN or LN event had occurred.

Shapiro (1987) looked at the impacts of the EN events that occurred during 1975-1985 on NATL activity in August-October. Shapiro identified EN events using an EN index based on SST anomalies in the eastern equatorial Pacific (the Nino 1 and 2 regions; see Weare 1986).

Goldenberg and Shapiro (1996) used the same index for a study on the relationships between west African rainfall, EN events, and NATL TC activity. Goldenberg and Shapiro did not specify which years they used to represent EN events.

Avila et al. (2000) compared the 1996 and 1997 NATL TC seasons in a study of the relationship between the number of tropical storms of African origin and the total number of tropical storms. They assumed that the relationship during 1997 was representative of the relationship during EN events.

In all of these studies the connections between NATL TC activity and EN events were studied, using a variety of methods to identify the EN periods, and using a number of different EN events, ranging from pre-satellite events to events during the early 1990s, and from an unspecified number of EN events to just one event. Also, in all these studies, LN events were either merged with all non-EN events, or not addressed at all.

2. Analyses and Major Results From Prior Studies

Gray (1984) found a negative correlation between moderate and strong EN events and the number of tropical storms and hurricanes. He also found that

tropical cyclone frequency is slightly above normal in non-EN years. Gray (1984) found that, during the EN events he examined, there were anomalously strong upper tropospheric westerlies over the Caribbean and western equatorial Atlantic that caused an anomalous increase in vertical wind shear that was unfavorable for TC development and maintenance in these regions of the NATL basin. Gray attributed these wind and shear anomalies to the outflows from anomalously strong convection in the eastern Pacific during EN events.

Gray (1984) also found a suppression of westward tracking NATL TCs equatorward of 20°N and a decrease in major hurricane (MH) landfalls during EN events compared to non-EN events. Several other studies have found reduced TC activity, fewer westward tracking TCs during EN events, and fewer U.S. landfalls during EN periods compared to all other periods (e.g., Lander at al. 1998, Pasch et al. 1998).

Gray (1994) found evidence that more TCs have formed to the north (south) of 25°N during EN (other) periods. Pasch et al. (1998), in an observational study of the 1994 and 1995 TC seasons, suggested that during EN periods a large percentage of TC formations may be from frontal zones and cold lows, rather than tropical waves, compared to non-EN periods.

Goldenberg and Shapiro (1996) termed the region bounded by 10°N, 20°N, the west coast of Africa, and Central America the main development region (MDR) and concluded that the vertical shear in this region is a critical determinant in MH activity. They also found that eastern Pacific SST and rainfall in the western Sahel are correlated with each other and with NATL TC activity,

with: positive (negative) SSTAs and negative (positive) rainfall anomalies corresponding to decreased (increased) TC activity. They proposed that the reason for the link between rainfall and TC activity is that the Sahelian convection alters the vertical shear in the MDR, with strong (weak) shear associated with strong (weak) convection. Shapiro (1987) found that there is not a clear EN impact on upper level vorticity in the MDR.

Gray et al. (1992) and Landsea (1991) found that a number of regional and global factors were statistically related to TC activity, including EN and LN events, Gulf of Guinea rainfall, and African monsoon circulation and moisture variables.

Ford (2000) identified anomalous wave trains extending eastward from East Asia and the western tropical Pacific into the North Atlantic during EN and LN events that he speculated could lead to a reduction (an increase) in vertical shear and an increase (a decrease) in TC formations in the subtropical NATL during EN (LN) events. Ford (2000) also identified differences between EN and LN periods in the vertical shear over the tropical NATL that appeared to be due to differences in the upper level easterly flow in that region.

E. EN AND LN EVENTS AND THE ASIAN MONSOON

Numerous studies have found strong correlations between EN and LN events and the intensity of the Asian summer monsoon (e.g., Rasmusson and Carpenter 1983, Joseph et al. 1994). Generally, monsoon precipitation and convective heating over South and East Asia are weaker (stronger) than normal

during the summer in which an EN (LN) event is building toward its maximum intensity (Meehl 1993). These convective heating anomalies lead to alterations of the upper tropospheric heights and winds, including a weakening (strengthening) of the tropical easterly jet (TEJ). Nigam (1994) found in a modeling study that Asian summer monsoon heating anomalies may regulate large-scale moisture fluxes into the Sahel. Thus, changes in the Asian monsoon may link EN and LN events in the tropical Pacific to NATL TC activity via processes occurring over northern Africa.

F. EN AND LN INDICES

Several indices have been developed to monitor the state of EN and LN events in the tropical Pacific (Philander 1990). One of the most widely used and familiar of these is the Southern Oscillation Index (SOI) (Ford 2000). The SOI is calculated by subtracting the sea level pressure anomaly (SLPA) at Tahiti from the SLPA at Darwin, Australia. The NINO3 index is a measure of the SSTAs in the eastern equatorial Pacific within a region bounded by 5S, 5N, 150W, and 90W. The Northern Oscillation Index (NOI), developed by Schwing et al. (2000), is calculated by subtracting the SLPA at the annual mean position of the North Pacific High (35N, 135W) from the SLPA at Darwin. The NOI is an indicator of the role of the North Pacific in EN and LN events.

The Multivariate ENSO Index (MEI, Wolter and Timlin 1998) monitors EN and LN using six environmental variables. Unlike the SOI, NINO3, and NOI, which are based on one variable (SLPA or SSTA) at one or two locations, the MEI incorporates sea level pressure, zonal and meridional surface winds, sea

surface temperature, surface air temperature, and total cloudiness fraction over most of the tropical Pacific. Thus, the MEI provides a more broadly based measure of the overall state of the tropical Pacific atmosphere and ocean than do the SOI or NINO3 index. EN and LN events occur over a very large region of the tropical Pacific. EN and LN events can vary considerably in their intensities, spatial extents, temporal evolution, and location of maximum anomalies. Therefore, a broadly based index such as the MEI may be desirable for fully describing EN and LN events.

MEI values are available from 1950. Fig. 2 shows the variations of the MEI through 2000. These variations are similar to those of the SOI, NINO3, and NOI, with all of these indices agreeing on the identification of moderate and strong events, but disagreeing on some weak events. The MEI shows that EN and LN events tend to start in the northern spring, in about May. LN events tend to reach their maximum intensity in about the following October. EN events tend to reach their peak in about January, about eight months after they began. Both EN and LN events tend to end about one year after they began, in the following northern spring. Fig. 3 shows the evolution of several strong individual EN and LN events.

Since EN and LN events span two calendar years, it is possible that they could affect two northern hemisphere TC seasons: the TC season that begins about the time that EN and LN events begin, or the next TC season. Since the first of these two seasons is more nearly simultaneous with EN and LN events, it is likely that EN and LN impacts on TCs would be greatest during this first TC

season. Ford (2000) found that this was true in his study of EN and LN impacts on western North Pacific TCs. In addition, since EN and LN events often immediately follow each other (see Fig. 2), the impacts during the second of these two TC seasons may be opposite to those during the first season, or a combination of both EN and LN impacts. Thus, it is important that studies of EN and LN impacts on TCs clearly identify which of these two seasons is being studied. Also, if both seasons are considered, the impacts during the two seasons should be separately analyzed.

Previous studies of EN and LN impacts on TCs have used a variety of global and regional indices to identify EN and LN event periods, and other periods in which neither an EN event or a LN event occurred. Table 1 lists the EN and LN event years identified by several indices and used in several prior studies of EN and LN impacts on TCs. For the entries in the Climate Prediction Center (CPC, 2000) column in Table 1, we replaced the CPC terms warm event and cool event with EN and LN event, respectively, following the terminology used in most of the related studies of NATL TCs.

Year	MEI	CPC	SOI	NOI	Gray 1984	Gray et al. 1993	Goldenberg and Shapiro 1996	Ford 2000
70	LS	LM	LS	LS		L	L	L
71	LS	LW	LM	LM		L	L	L

72	ES	EM	EM	EM	ES	E	ES	E
73	LS	LM	LVS	LM		L	L	L
74	LS	LW	LW	LM		L	L	L
75	LS	LM	LS	LS		L	L	L
76	EW	EW	LW	LS	EM	E	EM	
77	EM	EW	EM	ES		E	L	
78	EW			LW		L	L	
79	ES			ES		L	EM	E
80				EW		E	L	
81			LW	EW		L	L	
82	EES	EM	EVS	EVS	ES	E	EVS	E
83		EW	LW	LM	ES	E	EVS	
84	LM	LW	LW	LS		E	L	
85		LW	LW	EM		E	L	
86	EVS	EM	ES	EM		L	EW	E
87	EM	ES		LW		E	EM	

88	LS	LM	LS	LS		L	L	L
89		LW		LW		L	L	
90		EW		LM		L	L	
91	EVS	EM	EM	ES				E
92	EM	EM	EM	EM			EW	
93	EW	EM		LW				
94	ES	EM	EM	EM				E
95	LW	LW	LW	EW				
96	LW		LM	LW				
97	EVS	ES	ES	ES				E
98	LS	LW	LM	LS				L
99	LM	LW	LM	LM				

Table 1. EN and LN events as identified by different indices and selected studies of EN and LN impacts on TCs. The years shown in the left column refer to the year in which an EN or LN event began (e.g., 1982 refers to the year in which the 1982-1983 EN event began). The letters in the columns to the right of the left column indicate whether an EN or LN event occurred and, if so, what its intensity was, according to the indices and authors shown. Key to letters: first letter: L=LN, E=EN; following letters: W=weak, M=moderate, S=strong, VS=very strong, ES=extremely strong.

Table 1 shows that different indices and authors have come up with different determinations of the occurrence and intensity of EN and LN event periods and other periods. For example, Gray (1984), Gray et al. (1993) and Goldenberg and Shapiro (1996) identified 1983-1984 as a strong EN period. But 1983-1984 was a weak LN period according to the MEI, CPC, and SOI, and a moderate LN period based on the NOI. As another example, Gray (1993) and Goldenberg and Shapiro (1996) identified 1978-1979 as a LN period, based on Weare (1986). However, 1978-1979 is described as a non-event by the MEI, CPC, and SOI, and as a weak LN period by the NOI. A comparison of the Gray et al. (1993) and Goldenberg and Shapiro (1996) columns in Table 1 shows that a number of periods were identified as EN periods in one study but as LN periods in the other study. Obviously, such discrepancies could lead to conflicting results about the impacts of EN and LN events. Just why these discrepancies occurred is not clear, since a number of studies did not fully describe their identification procedures. One obvious reason for the discrepancies may be that the different indices were used. Another reason may be that the periods of the year for which the index values were analyzed may have been different.

G. DESIGN OF THIS STUDY

This study was designed to help overcome the following limitations and inconsistencies of previous studies.

1. Most prior studies used indices for event identification that are based on a single variable at only one or two locations in the tropical Pacific. Many prior studies have not clearly identified

their event selection procedure, including whether they were analyzing impacts during the first or the second TC season associated with an EN or LN event. In addition, most prior studies identified EN and LN events based on the maximum intensity reached by an index of EN and LN events. But the maximum intensity is generally reached at the end of, or after, the Northern Hemisphere TC seasons. So this identification procedure may exclude some events that peaked early and were strong during the TC season, while including events that peaked late and were weak during the TC season. In this study, we used the broad-based MEI during the NATL TC season to identify EN and LN events. This method is described in Chapter II.

2. Most previous studies have focused on the impacts of EN events only. TC activity during EN events has often been compared to TC activity during all other times, including LN event and non-event periods. Identifying the differences between EN and LN periods could add to the determination of how TC activity is altered during these events. Prior studies of EN and LN events have shown that the strongest anomalies during these events are generally opposite to each other (Barnston et al. 1999). So in identifying what environmental changes can be attributed to EN and LN events, it is useful to consider both EN and LN, and

the differences between EN and LN periods. In this study, we analyzed and compared TC activity during EN and LN events.

3. Some studies of EN and LN impacts on NATL TC activity have analyzed a relatively small number of EN and/or LN events, or unequal numbers of EN and LN events. In this study, we have analyzed TC activity during a total of 20 events (ten EN events and ten LN events) in order to identify the characteristic features of NATL TC activity and the related large scale circulation during EN and LN events.

4. Many prior studies have analyzed TC activity that occurred before extensive satellite observations became available in the mid-1970s. Lander (1994) suggests that analyses of TC activity may be significantly different when satellite data are included. To minimize this problem, we focused our analyses on EN and LN periods that occurred after 1973. We did however, include one EN event and three LN events that occurred during 1970-1973, in order to increase our sample size, and to come as close as possible to a balance in the intensities of the EN and LN events being analyzed (see Chapter II for more on this issue).

5. During 1991-1999, there were a number of very well observed EN and LN events that occurred after most of the prior studies were conducted. In this study, we have included four EN events and two LN events from 1991-1999.

6. Most prior studies of EN and LN impacts on TC activity have been mainly statistical in nature, with little or no analysis of the dynamical mechanisms that created these impacts. In this study, we analyzed the basin and global scale circulation anomalies associated with EN and LN events and their roles in altering TC activity. In particular, we have used teleconnection concepts to link EN and LN related processes in the tropical Pacific and Asian monsoon regions to changes in North Atlantic circulations and TC activity.

Our main goal in this observational study was to clarify the role of EN and LN events in North Atlantic tropical cyclone activity. To do so, we focused on answering two main questions:

1. How was TC activity different during past EN and LN events?
2. What mechanisms caused these differences to occur?

Our hypotheses for this study were based on a number of previous studies, especially Ford (2000) and preliminary work on the tropical easterly jet (TEJ) that we conducted as part of course work at the Naval Postgraduate School. Our two main hypotheses were:

1. EN and LN events play a role in creating anomalous quasi-stationary wave trains that extend from East Asia and the western tropical North Pacific into the North Atlantic during the latter half of the North Atlantic TC season. These anomalous wave trains tend to produce circulation

anomalies in the North Atlantic that are opposite during EN and LN events. These lead to differences between EN and LN events in the vertical shear and steering flow, which lead to differences in TC formation sites, numbers, intensities, and tracks.

2. EN and LN events produce opposite changes in the intensity and westward extent of the tropical easterly jet in the middle and upper troposphere over northern Africa. This leads to a weaker (stronger) jet with a lesser (greater) westward extent during EN (LN) events. This in turn leads to opposite alterations of the vertical shear in the tropical North Atlantic basin, thereby altering the formation sites, numbers, intensities, and tracks of TCs in the tropical NATL.

H. ORGANIZATION

In the following chapter, our data and methods are presented. Chapter III presents our main results. Chapter IV provides our summary of results, discussions and conclusions, and suggestions for future research.

II. DATA AND METHODS

A. DATA

Much of the data used in the study was from the National Centers for Environmental Prediction (NCEP) reanalysis data set, obtained through the NOAA-CIRES Climate Diagnostic Center (CDC) web site at http://www.cdc.noaa.gov. The reanalysis data used were monthly mean fields of several atmospheric and oceanic variables, at a 2.5° latitude by 2.5° longitude resolution. The reanalysis data set is derived from historical observations that have been analyzed with a modern version of the NCEP global data assimilation system. Details on the reanalysis data can be found in Kalnay et al. (1996) and at http://www.cdc.noaa.gov/cdc/data.nmc.reanalysis.html

The North Atlantic TC best track data, including date, time, central location, and intensity (maximum 1-minute surface wind speeds) for all reported TCs, was obtained from the National Hurricane Center (NHC) in Miami, Florida. TC information was based on information obtained from aircraft reconnaissance, satellite interpretation, and surface observation report. Tropical observations increased dramatically in the 1970's with the integration of meteorological satellite coverage, along with a satellite derived intensity estimation method (Dvorak 1975). Because of the increased observations, and more uniform intensity estimates, TC best track information appears to be more consistent after 1974. (Lander 1994)

B. EVENT IDENTIFICATION

As discussed in Chapter I, many different indices have been used to represent the occurrence and intensity of EN and LN events. We have used the Multivariate ENSO Index (MEI) (Wolter and Timlin 1993) in this study because it provided a comprehensive depiction of EN and LN events across most of the tropical Pacific and in terms of several variables. The MEI is based on the following six tropical Pacific fields: sea level pressure, zonal surface wind, meridional surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. These fields are derived from the Comprehensive Ocean-Atmosphere Data Set (COADS). The MEI is computed separately for each of twelve sliding bi-monthly seasons (Dec/Jan through Nov/Dec). After spatially filtering the individual fields into clusters (Wolter 1987), the MEI is calculated as the first unrotated principal component of all six fields combined. The bi-monthly values are standardized according to the season and and the 1950-1993 reference period. Positive values of the MEI represent EN events and negative values represent LN events.

The MEI was used in this study to identify EN and LN events during 1970-1999 and to classify these events according to their strength. To do so, we first calculated the average June/July-October/November MEI value for each of the 30 years. This averaging period was chosen to determine the intensity of the EN and LN events during the NATL TC season (June-November). The bi-monthly values and the June/July - October/November seasonal average for each year are shown in Table 2.

YEAR	JUN/JUL	JUL/AUG	AUG/SEP	SEP/OCT	OCT/NOV	J/J-O/N AVE
1970	-1.123	-1.019	-1.238	-1.096	-1.087	-1.1126
1971	-1.238	-1.259	-1.457	-1.442	-1.384	-1.356
1972	1.811	1.761	1.571	1.628	1.72	1.6982
1973	-1.072	-1.355	-1.699	-1.664	-1.474	-1.4528
1974	-0.777	-0.698	-0.617	-0.998	-1.199	-0.8578
1975	-1.491	-1.672	-1.816	-1.931	-1.747	-1.7314
1976	0.609	0.72	1.023	0.916	0.443	0.7422
1977	0.843	0.689	0.779	0.988	0.987	0.8572
1978	-0.351	-0.218	-0.354	-0.002	0.241	-0.1368
1979	0.352	0.637	0.805	0.696	0.757	0.6494
1980	0.814	0.357	0.283	0.203	0.252	0.3818
1981	0.004	-0.153	0.118	0.121	-0.007	0.0166
1982	1.591	1.753	1.794	2.027	2.458	1.9246
1983	1.791	1.249	0.525	0.065	-0.12	0.702
1984	-0.215	-0.233	-0.059	0.025	-0.309	-0.1582
1985	-0.226	-0.408	-0.523	-0.125	-0.048	-0.266
1986	0.382	0.69	1.098	1.013	0.859	0.8084
1987	1.825	2.033	1.887	1.648	1.247	1.728
1988	-1.243	-1.334	-1.555	-1.363	-1.476	-1.3942
1989	-0.457	-0.572	-0.299	-0.347	-0.064	-0.3478
1990	0.098	0.106	0.425	0.314	0.367	0.262
1991	0.989	0.939	0.655	1.001	1.166	0.95
1992	1.003	0.626	0.492	0.595	0.523	0.6478
1993	1.109	1.036	1.012	1.044	0.841	1.0084
1994	0.817	0.584	0.653	1.337	1.227	0.9236
1995	0.278	0.064	-0.352	-0.423	-0.475	-0.1816
1996	-0.182	-0.255	-0.309	-0.369	-0.105	-0.244
1997	2.623	2.868	2.819	2.205	2.339	2.5708
1998	0.345	-0.162	-0.562	-0.799	-1.06	-0.4476
1999	-0.535	-0.749	-0.875	-0.932	-1.037	-0.8256

Table 2. MEI values for the bi-monthly periods June/July through October/November, along with the June/July – October/November average MEI for each year during 1970-1999.

The June/July – October/November seasonal averages shown in Table 2 were then used to classify each year. Periods with seasonal averages greater

than or equal to +0.25 were classified as EN periods, while periods with seasonal averages less than or equal to -0.25 were classified as LN periods. Wolter and Timlin (1993) used a bi-monthly MEI magnitude of 0.3 as the threshold for determining whether an EN or LN event occurred. We lowered that threshold slightly, to 0.25, because the June-November TC season in the NATL occurs prior to the period of maximum intensity for EN and LN events (see Chapter I). Our event identification procedure is an objective method based on the MEI. Other studies using other procedures have come up with similar results. For example, CPC uses a procedure based on reanalyzed SSTs in the equatorial Pacific between 150W and the dateline and gets results that are very similar to those in Table 2 for all but the weakest events (CPC 2000).

C. EVENT SELECTION

In this study, we have attempted to identify the characteristic features of NATL TC activity and the related large scale circulation during EN and LN events. To do so, we wanted to select EN and LN events that would allow us to meet four somewhat conflicting objectives: (a) analyze the maximum number of events (i.e., increase our sample size); (b) analyze the events with the greatest intensity (i.e., increase the likelihood of a large signal to noise ratio in our results); (c) analyze an equal number of EN and LN events (i.e., make the EN and LN event observations and composites more comparable); and (d) analyze events during the satellite era (i.e., work with the most complete data sets). Since not all of these objectives can be simultaneously met, we struck a balance by selecting the ten strongest EN and ten strongest LN events in Table 2 as the focus events for this study. The 20 event years we selected are listed in Table 3.

EN Event years	LN Event years
1972	1970
1976	1971
1977	1973
1982	1974
1986	1975
1987	1985
1991	1988
1993	1989
1994	1998
1997	1999

Table 3. List of EN and LN periods focused on in this study. The years indicate the first year of EN and LN events (e.g., 1997 indicates the first year of the 1997-1998 EN event).

The EN and LN periods in Table 3 have all been identified as such in previous studies using alternate identification procedures (Wolter and Timlin 1993, Schwing et al. 2000, CPC 2000), although some studies differ in their analyses of the periods with the weakest MEI values (e.g., 1985 and 1989).

To determine the effects of limiting our main study to the events shown in Table 3, we conducted analyses using several alternate sets of years (e.g., using, from Table 2: all 15 EN events and all 10 LN events, just the five strongest EN and LN events, just the five weakest EN and LN events, etc.). We found that

our major results (described in Chapter III) were not substantially altered when using these different event sets. However, the interpretation of the results was more straightforward when using the events listed in Table 3, since using this set of events balances out the advantages of using a large number of events (samples), the strongest events, and an equal number of events.

According to our threshold magnitude of 0.25, there were 15 EN events and 10 LN events during 1970-1999. Thus, only five of the 30 years listed in Table 2 were neither EN nor LN periods. Examination of the seasonal average values in Table 2 show that the strongest EN events had considerably greater MEI absolute magnitudes than the strongest LN events. Several studies have found that that there have been more EN events than LN events since 1970 (and especially since 1976), and that the strongest EN events have been more intense than the strongest LN events over the last 50 years (e.g., Wolter and Timlin 1993, Schwing et al. 2000). The reasons for these differences between EN and LN events are not clear, but may reflect long term trends in the observations, decadal oscillations of the climate system, biases in the climatological values used to calculate anomalies, or a failure of climate indices to completely represent LN patterns (cf. Schwing et al. 2000).

We considered using events prior to 1970 in order to increase the number of events, especially LN events, that could be analyzed. We decided not to do so because of the smaller number of observations of both TCs and the large-scale circulation during earlier years. Also, a preliminary review of the EN and LN

events that occurred prior to 1970 showed some questionable features in the NCEP reanalysis fields over the South Pacific and Indian Ocean regions.

Our focus set (Table 3) includes the LN events of 1970-1971, 1971-1972, and 1973-1974 that occurred prior to extensive satellite observations. We decided to use these events in order to increase the number of strong LN events in our focus set. We conducted analyses in which these three LN events were excluded and found that our major results (see Chapter 3) were not substantially altered. But, as stated earlier, the comparisons of EN and LN event observations and composites were more straightforward when the full set of events shown in Table 3 was used.

EN and LN events span two calendar years, and therefore may affect the TC seasons that occur before and after the events reach their peak (see Chapter I). However, our initial analyses of NATL TC activity during these two seasons showed that the differences between EN and LN periods were much greater during the first of these two seasons. Ford (2000) reached a similar conclusion. Therefore, we focused our study on the first of these two TC seasons.

D. ANALYSIS

1. Composites and Anomalies

Composites based on the 10 EN periods and 10 LN periods listed in Table 3 were used to identify characteristic EN and LN patterns. For example, to find the characteristic 200 hPa zonal winds for October during EN events, the 200 hPa zonal winds for October of each EN year listed in Table 3 were averaged. EN and LN anomalies were also calculated by subtracting long term mean values

from the EN or LN composite values. For example, to calculate the EN composite 200 hPa height anomaly for August, the EN composite 200 hPa height for August was subtracted from the long term mean 200 hPa height for August. The long term means were based on 1968-1996, which is also the long term mean period used by the Climate Diagnostic Center. We also averaged together several months within the TC season (June-November) to define representations of the TC activity and environmental conditions during different portions of the TC season; for example, July-September (JAS) and September-November (SON).

2. Vertical Shear

The vertical shear of the zonal wind was calculated by subtracting the 850 hPa zonal wind from the 200 hPa zonal wind. Vertical profiles of the zonal wind were also created using 200hPa and 850hPa winds from the EN and LN composites and the long term mean. Steering winds for TCs were determined using primarily the winds at 500 hPa.

3. TC Activity

Best-track TC data were analyzed to define EN and LN composites of: (1) average number of all TCs per month, (2) average number of major hurricanes (>100kts maximum sustained winds) per month, (3) average TC intensity per month, and (4) average number of TCs reports per month (a measure of forecaster activity).

In analyzing TC formations, we assigned each TC to the month in which it was first reported. Average TC intensity per month was based on the actual days on which the TCs were active. For an example, TS Amber may have

formed on 29 July and dissipated on 7 August of that same year. TS Amber is counted as a TC that formed in July, but the intensity is reported in July and August respectively.

TC tracks and formation sites were plotted using best track location information. These plots were analyzed to identify characteristic formation and track patterns associated with EN and LN events.

E. REGION SELECTION

Our analyses of TC formations (see Chapter 3) led us to identify five regions of the North Atlantic in which clear differences in formations and related environmental factors existed between EN and LN events. They include: a tropical region near West Africa (abbreviated as WAF), a central tropical Atlantic region (TATL), a western Caribbean region (WCAR), a subtropical central Atlantic (SATL), and a Gulf of Mexico region (GOMEX). The locations of these regions are given in Table 4 and in Fig. 4.

Region	Latitude	Longitude
Tropical West Africa (WAF)	8N – 18N	25W – 12W
Tropical Central Atlantic (TATL)	8N – 18N	55W – 35W
Western Caribbean (WCAR)	8N – 23N	90W – 70W
Subtropical Central Atlantic (SATL)	19N – 28N	65W – 45W
Gulf of Mexico (GOMEX)	25N – 32N	99W – 81W

Table 4. Regions in the North Atlantic, Caribbean, and Gulf of Mexico used to highlight differences in TC activity and environmental conditions between EN and LN periods.

III. RESULTS

A. TIME SERIES OF TC BEST TRACK DATA

The time series plots were created in order to determine, for both the EN and LN composites, the number of tropical cyclones per month, the average intensity per month, and the average number of TC reports. The number of TCs per month was calculated for the following intensities: ≥ 25 kts, ≥ 35 kts, ≥ 64 kts, and ≥ 100 kts. These intensities correspond to TCs of tropical depression (TD), tropical storm (TS), hurricane (H), and major hurricane (MH) intensity, respectively.

1. Numbers of TCs

The average number of tropical cyclones per month with TD intensity or greater is shown in Fig. 5. The months on the horizontal axis represent January-December of the EN and LN periods listed in Table 3, which represent the first TC season of each event. Notice that the composite and LTM curves have similar shapes, with most TCs occurring during June-November, and the largest number occurring in September. For most months, the LN number of TCs is greater than the LTM number, which in turn is greater than the EN number. The LTM numbers are generally about half way between the EN and LN numbers. This indicates that EN and LN events create extremes in the numbers of TCs, and that these extremes are approximately symmetric about the LTM. This result also indicates that the years during 1970-1999 that are not part of the EN and LN

composites (the years not listed in Table 3) represent climatological conditions, at least in terms of TC numbers.

We also calculated the numbers of TCs per month with TS, H, and MH intensities for the EN and LN composites and the LTM. These numbers are not shown graphically, because they are very similar to the results shown in Fig. 3-1. In particular, at all intensities and for almost all months, the LN composite number of TCs is greater than the LTM number, which is greater than the EN number. The average numbers of TCs with TD, TS, H, and MH intensities in the EN and LN composites and in the LTM are shown in Table 5. The numbers are based on May-December, although most of the activity occurred during June-November (Fig. 5). Table 5 also shows the percent difference between EN and LN events, calculated as $\frac{LN_{no.ofTCs} - EN_{no.ofTCs}}{LN_{no.ofTCs}} \times 100$.

	EN	LN	LTM 1970-1999	% difference between EN and LN
TD (≥ 25 kts)	8.4	11.9	10.7	29%
TS (≥ 35 kts)	7.3	11	9.7	33%
H (≥ 64 kts)	3.7	6	5.4	38%
MH (≥ 100 kts)	0.9	2.5	1.9	64%

Table 5. Average number of TCs of TD, TS, H, and MH intensity in the EN and LN composites and in the LTM, along with the percent differences in these numbers between EN and LN events (see the accompanying text for how this difference was calculated). Averaging period: May-December.

Table 5 shows that the LN composite has higher numbers of TCs at all intensities than the LTM, which has more than the EN composite. Table 5

indicates that a TC season that occurs during a LN event is likely to have one-third more TDs, TSs, and Hs, and two-thirds more MHs than is a TC season that occurs during an EN event.

2. TC Intensities

The average TC intensities per month for the EN and LN composites and the LTM are shown in Fig. 6, for TCs of TD or greater intensity. For most months, the LN intensities are greater than the LTM intensities, which in turn are greater than the EN intensities. Notice that LN events had an average TC intensity greater than hurricane intensity, with the exception of June, while EN events had an average TC intensity less than hurricane intensity, with the exception of August.

As in Fig. 5, the LTM intensities lie between the EN and LN intensities. This result, along with a similar results shown in Fig. 5, indicates that EN and LN events create extremes in TC intensities, and that the years during 1970-1999 that were excluded from the EN and LN composites represent climatological conditions in terms of TC numbers and intensities.

Fig. 6 also shows that June was an exception, with greater TC intensities in the EN composite than the LN composite. This is related to the larger number of June TCs in the EN composite than the LN composite (Fig. 5) and will be discussed further in the following section on formation site differences.

3. Summary of Time Series Results

Figs. 5 and 6 show that there tends to be, throughout a TC season and compared to the LTM, a large number of strong TCs if a LN event is occurring, and a small number of weak TCs if an EN event is occurring.

B. TC FORMATIONS

As shown in Fig. 5, the largest monthly differences in TC formations occurred in the middle (July-September) and in the end (September-November) of the TC season (Fig. 5). To analyze the spatial patterns associated with these temporal patterns in TC formations, we created EN and LN composite monthly maps showing the formation sites for all the TCs that occurred during the EN and LN periods (not shown). These monthly spatial patterns were similar for the middle and late months of the TC season. Thus, we grouped the EN and LN composite formations into two three-month periods: July-September, in the middle of the TC season, and September-November, late in the TC season. The monthly formation maps also showed that the major formation differences occurred in five regions of the North Atlantic basin (see Table 4), so we focused our analyses of formation differences on these regions. Fig. 7 - 9 show all of the NATL formation sites for the EN and LN composites during July-August-September (JAS) and September-October-November (SON), with the five regions outlined.

These Fig.s also show the corresponding vertical shear of the zonal wind ($U_{200} - U_{850}$), SSTAs, and outgoing longwave radiation anomalies (OLRAs). We compared these three fields with the formation sites in Figs 7 – 9 to determine if

they might have been factors in producing the formation differences. As discussed in the following sections, we found that each of these fields was a likely factor, for certain periods and regions. The vertical wind shear Fig.s (Fig. 7) also show the anomalous 200 hPa geopotential heights, to clarify the EN-LN differences in vertical wind shear.

We did however analyze several other variables that are known to affect TC formations, including: SST > 26°C; winds and geopotential heights at 850, 700, and 500 hPa; and relative vorticity at 850 and 200 hPa. We found that the roles played by these variables in producing the major formation differences were secondary to those of vertical wind shear, SSTA, and OLRA. For example, we concluded that the SST > 26°C threshold (Gray 1968) was probably not a factor, since the regions in which EN-LN formation differences occurred had SSTs that were at or above 26°C in both the EN and LN composites. (Note: almost all the formations in both the EN and LN composites occurred in areas where the composite SST was greater than or equal to 26°C.)

1. July-August-September (JAS)

a. West Africa (WAF)

Fig. 7 shows that there were more formations in JAS in the west African region during LN events than EN events. The vertical wind shear was relatively favorable for formations over most of this region (shear magnitude < 10 m/s) during both the EN and LN events, but somewhat weaker and more favorable during the EN events. Thus, the vertical wind shear does not seem to explain the larger number of formations in this region during LN events. Similarly, the SSTAs (Fig. 8) do not appear to explain the WAF formation

differences, since in the EN composite positive SSTAs were associated with fewer formations, and in the LN composite negative SSTAs were associated with more formations.

However, EN and LN composite OLRAs during JAS were consistent with the WAF formation differences (Fig. 9). These anomalies were strong and opposite to each other in and near the WAF region. In both composites, the WAF OLRAs were part of anomaly features that were centered over the nearby continental areas of Africa, especially the western Sahel at about 10-17°N. The negative OLRAs in the LN composite indicate that anomalously strong deep convection occurred during the LN events over the western Sahel and nearby regions. Such convection anomalies may have contributed to the development of regional scale circulations and convective systems that were favorable for TC formation in the WAF region (cf. Gray et al. 1993, McBride 1995). The corresponding EN composite OLRAs were positive, indicating that a relative absence of deep convection over the tropical western Sahel may have inhibited TC formation during the EN periods. Note too that the strong and opposite nature of the western Sahelian OLRAS in the EN and LN composites suggest that these OLRAs are especially characteristic of EN and LN events (see Chapter 1; Gray et al. 1993).

b. Tropical Atlantic (TATL)

Fig. 7 shows that the central tropical North Atlantic had more TC formations in JAS during LN events than during EN events. The vertical wind shear appears to have been an important factor in producing these differences.

In the LN composite, almost all the region had a shear between –5 m/s and +10 m/s. In the EN composite, about two-thirds of the region had a shear in the +5-15 m/s range. Fig. 10 shows that most of the EN-LN difference in the vertical wind shear in the TATL region was due to anomalously strong upper-tropospheric easterly winds during LN events and a reversal of the climatological easterly flow during EN events. This is consistent with the 200 hPa height anomalies shown in Fig. 7.

The EN-LN difference in the number of TC formations in the TATL region during JAS is also consistent with the SSTA differences (Fig. 8). Thus, SST differences between EN and LN events may have contributed to the formation differences, with: positive (negative) SSTAs leading to more (fewer) formations in the TATL during LN (EN) events.

c. Gulf of Mexico (GOMEX)

In the Gulf of Mexico during JAS, more TC formations occurred during EN events than during LN events (Fig. 7). Fig. 8 shows that anomalousl high SSTs during EN events, and anomalous low SSTAs during LN events, may have contributed to these differences. Vertical wind shear may also have been a factor, since it was lower somewhat lower during the EN events (Fig. 7).

Fig. 5 shows that in June there were also more formations in the GOMEX region during EN events. EN and LN composite maps of TC formations and SSTAs for June (not shown) reveal positive (negative) SSTAs in the GOMEX during the EN (LN) events. Thus, the differences in SST may have been a factor

in producing the June formation differences, as well as the JAS formation differences.

d. *Subtropical Atlantic (SATL)*

In the subtropical Atlantic region during JAS, more TC formations occurred during EN events; in fact, there were no formations in this region during the LN events (Fig. 7). Lower shear during the EN events may have been a factor, with the EN composite having a lower minimum shear, and a larger area in which the shear was less than 10 m/s (Fig. 7). SST was probably also a factor, since there were positive SSTAs and more formations in the EN composite (Fig. 8).

2. September-October-November (SON)

During SON, four areas showed a large EN-LN difference in TC formations: the WAF, TATL, SATL, and WCAR regions.

a. *West Africa Region (WAF)*

As in JAS, the western Africa region during SON had more TC formations during LN events than during EN events (Fig. 11). The main contributing factor appears to have been OLRAs over western tropical Africa, as in JAS (Fig. 13). However, in SON, weaker vertical wind shear during LN events may have also contributed to the greater number of formations (Fig. 11). Note that the LN composite shear shows a larger area than during EN in which the shear was less than 10 m/s (Fig. 11).

b. *Tropical Atlantic (TALT)*

Fig. 11 shows that the central tropical North Atlantic had more TC formations in SON during LN events than during EN events. The vertical wind

shear appears to have been an important factor in producing these differences. In the EN composite, almost all the region had a shear greater than 15 m/s while in the LN composite, about half the region had a shear less than 15 m/s.

Unlike the situation in JAS, the EN-LN difference in the number of TC formations in the TATL region during SON is not consistent with the SSTA differences (Fig. 12). That is: the larger (smaller) number of formations during LN (EN) is inconsistent with the occurrence of anomalously cool (warm) SSTs during LN (EN).

Note that in the TATL during SON, all the EN and LN formations occurred under composite shears that were greater than 10 m/s, which suggests that from a synoptic perspective on TC formation, all the TCs formed under unfavorable shear conditions. However, when the EN and LN composite formations shown in Fig. 11 are plotted month by month (not shown), rather than in one three-month average, most of the formations during both the EN and LN events are found to have occurred in shear of 10 m/s or less. In this monthly perspective, the number of formations remained higher, and the shear remained lower, during the LN events. The reason the shear appears to be too high in the three-month composite is that, in the TATL, the shear increases rapidly at the end of the TC season, as the area of upper-tropospheric westerlies expands southward from the subtropics into the tropics (Palmen and Newton 1969). Fig. 11 (and the monthly versions of Fig. 11, not shown), reveal that during the LN events, the normal onset of high shear in the TATL was delayed, and summer-like low shear conditions persisted longer. During the EN events, the opposite

occurred. Thus, vertical shear differences do seem to have been important in creating the formations differences in the TATL during SON.

From a monthly perspective, most of the formations shown in Fig. 11 are consistent with the expected formation-vertical shear relationship. However, even in the monthly averages, some of the TC formations in the TATL during SON are found to have occurred in areas with shear greater than 10 m/s, and in some cases, greater than 15 m/s. This is probably an indication of vertical shear variations within the individual months, and between the individual months, that were used to create the EN and LN composites. The EN and LN composites average together months from ten different years, while the TC formations implicitly represent conditions within an individual month (and maybe just a few days of that month). So it is not surprising that there are some discrepancies between the conventional formation-vertical shear relationship and the relationships shown in the composites.

One conclusion from this is that the time averaging used in climate event analyses may introduce some inconsistencies between synoptic and longer term views of TC activity. When considering TC activity from a climate event perspective, some of the synoptic scale guidelines used to explain TC activity may need to be relaxed.

c. Western Caribbean (WCAR)

In the western Caribbean region during SON, more TCs formed during LN events than during EN events (Fig.11). This difference is consistent with lower shear and negative OLRAs in the region during LN events (Figs. 11-

13). The vertical profile of the zonal winds in the area indicates that the shear difference was due mainly to anomalous easterlies (westerlies) in the upper troposphere during LN (EN), consistent with the 200 hPa height anomalies shown in Fig. 11. This result is similar to a finding by Gray (1984). The negative (positive) OLRAs in the WCAR during LN (EN) may have helped increase (reduce) TC formations. But their regional scale extent suggests that they may be instead the response to the formation and resulting TC activity differences.

d. Subtropical Atlantic (SATL)

In the subtropical Atlantic region during JAS, more TC formations occurred during EN events (12 formations during EN events, two formations during LN events; Fig. 7). Lower shear during the EN events was likely a factor, with almost all the region having a shear between of 10-15 m/s in the EN composite, and much of the region having a shear greater than 15 m/s in the LN composite. The major reason for the shear differences is that during EN (LN) events, the upper-tropospheric zonal winds were anomalously easterly (westerly), as shown in Fig 14, and as implied by the 200 hPa height anomalies (Fig. 11). As in JAS, SST was probably also a factor, since there were positive SSTAs and more formations in the EN composite (Fig. 12).

The SATL region is in the subtropics, where TC formations associated with midlatitude frontal systems are relatively likely. However, the EN and LN composite 200 hPa height anomalies (Fig. 11), which are equivalent barotropic and extend to the surface (see Chapter I), indicate that the larger numbers of formations during EN events occurred in and near anomalously high

pressures. This suggests that in the SATL region, interactions with midlatitude frontal systems were weaker during EN events, and were probably not a factor in producing the larger number of formations. However, such interactions may help explain why the region west of the SATL and east of the southeastern U.S. had a larger number of formations during LN events than during EN events, despite having had a high vertical shear during LN events (> 15 m/s) that was higher than the vertical shear during EN events (see Fig. 11). The negative 200 hPa height anomalies (Fig. 11) indicate that in this region the circulation anomalies favored equatorward extensions of midlatitude cyclones.

3. JAS and SON TC Formation Summary

EN and LN events during 1970-1999 had clear impacts on TC formations. The major differences occurred in five regions of the NATL basin, and in JAS and SON, the middle and late periods of the NATL TC season. A summary of when and where these TC formation differences occurred, and of the variables that appear to have contributed to the differences, is shown in Table 6. Notice that the vertical shear of the zonal wind appears to have been a factor in creating TC formation differences in all the regions.

	GOMEX	SATL	WCAR	TATL	WAF
Vertical Shear	JAS	JAS SON	SON	JAS SON	SON
SSTA	JAS	JAS SON		JAS	
OLRA			SON		JAS SON

Table 6. Summary of the main factors that contributed to the EN-LN TC formation differences, according to the region and periods in which they contributed.

Because vertical shear was a factor in all the regions, we conducted a more detailed investigation into the causes of the differences in vertical shear between EN and LN events.

C. MECHANISMS TO EXPLAIN VERTICAL SHEAR

For all five regions listed above, vertical shear was a factor that could help to explain the differences in TC formations during EN and LN events. The vertical wind profiles (Figs 10,14) show that EN-LN differences in the 200 hPa winds were important in creating these shear differences. Fig. 15 shows the EN and LN composite 200 hPa height anomalies during JAS in the tropics and Northern Hemisphere. These global-scale height anomalies can be used to understand the processes that created the 200 hPa wind differences in the NATL. During the EN (LN) events, positive (negative) 200hPa height anomalies were present throughout the tropics, while the northern subtropics and midlatitudes were dominated by negative (positive) height anomalies. A number of other studies have also found that these height anomalies are characteristic of EN and LN events, with the tropical height anomalies reflecting the equatorial Rossby-Kelvin wave response to anomalous tropospheric heating (Bjerknes 1969, Horel and Wallace 1981, Philander 1990, Matsuno 1966, Gill 1980).

Anomalous wind patterns can be inferred from the anomalous height anomalies. Specifically, anomalous cyclonic winds are indicated by anomalous negative (lower) height anomalies, and anomalous anticyclonic wind anomalies are indicated by anomalous positive height (higher) height anomalies. Thus, Fig. 15 can be used to identify a region of anomalously westerly (easterly) winds at

200 hPa that extends around the globe at about 10-35°N in the EN (LN) composite. Over the tropical NATL, these winds represent an increase (a decrease) in the western extent of the tropical easterly jet that is centered over tropical northern Africa (Palmen and Newton 1969). Analyses of height and wind anomalies from 200 hPa to the surface (not shown) indicate that similar variations of the easterly flow occur throughout the middle and upper-troposphere from the tropical NATL into the Indian Ocean.

The height and implied wind anomalies in Fig. 15 are consistent with the vertical wind profiles shown in Figs. 10 and 14. Thus, the vertical wind shear differences that help explain formation differences during JAS (see Chapter 3, section B) were derived from global height anomalies that develop during EN and LN events. In the tropical North Atlantic, these height anomalies led to variations of the upper tropospheric winds, especially the westward extent of the tropical easterly jet, such that the vertical shear was increased (reduced) during the EN (LN) events. These globally-derived changes in shear appear to have been especially important in altering TC formations in the TATL region.

Fig. 16 shows the EN and LN composite 200 hPa height anomalies during SON in the tropics and northern hemisphere. During the EN (LN) events, there were positive (negative) 200hPa height anomalies throughout the tropics, while much of the northern subtropics and midlatitudes were dominated by negative (positive) height anomalies. As in JAS, the 200 hPa wind anomalies (inferred from Fig. 16) were westerly (easterly) over the tropical NATL during EN (LN),

which led to increased (reduced) vertical shear and reduced (increased) TC formations in the TATL and WAF regions (see Chapter III, section B).

However, unlike JAS, during SON, there was a strong positive (negative) 200 hPa height anomaly over the subtropical North Atlantic during the EN (LN) events. These subtropical North Atlantic height anomalies are part of anomalous wave trains emanating from East Asia and the western tropical Pacific that are very similar to the ones described by Nitta (1987) and Ford (2000). Other studies (e.g., Ford 2000, Schwing et al. 2000) have also found that these anomalous wave trains are characteristic features of EN and LN events, especially during September-January. As discussed in the preceding section, the EN and LN composite 200 hPa height anomalies during SON in the subtropical NATL are consistent with the corresponding vertical shear and upper tropospheric zonal wind differences that appear to explain the formation differences in the SATL region. Thus, the anomalous wave trains from East Asia and the western tropical Pacific appear to be a mechanism by which EN and LN events affect NATL TC activity. The processes by which EN and LN events generate these wave trains are discussed by Ford (2000).

Fig. 16 also shows that during the EN (LN) events, there were anomalously positive (negative) heights in the central tropical Pacific that are symmetric about the equator. These were quasi-stationary Rossby waves that developed in response to the anomalous tropospheric heating in this region during EN and LN events (cf. Horel and Wallace 1981, Hoskins and Karoly 1981). These features extended into the western Caribbean where they caused

anomalous westerlies (easterlies), leading to anomalously high (low) vertical shear during the EN (LN) events. Thus, the Rossby wave response appears to have been a factor in creating the formation differences in the WCAR region (see Chapter 3, section B.2.c). These results are related to those of Gray (1984) who found Caribbean circulation and shear anomalies during EN events that he traced back to the eastern tropical Pacific. Our results suggest that the Caribbean anomalies that Gray found may be due to anomalous Rossby-Kelvin waves originating in the central tropical Pacific, and that similar but opposite events take place during LN events.

D. TROPICAL CYCLONE TRACKS

For the reasons discussed at the beginning of Chapter III, section B, we created monthly EN and LN composite maps showing the tracks for all the TCs that occurred during the EN and LN periods (not shown). The track differences were similar for the middle and late months of the TC season, so we grouped the EN and LN composite formations into two three-month periods: July-September, in the middle of the TC season, and September-November, late in the TC season. The monthly track maps also showed that the major track differences occurred in two regions of the North Atlantic basin, the Gulf of Mexico and along the east coast of the U.S. Thus, we focused our analyses of track differences on these two regions.

In addition to analyzing the TC tracks, we examined several other variables in order to characterize the track differences, and to determine the reasons for the track differences. These variables were: westernmost longitude

reached by TCs; TC formation sites with respect to the subtropical ridge; 500 hPa height anomalies; 500 hPa wind anomalies; and 200 hPa height anomalies. We used the westernmost longitudes to estimate EN-LN differences in landfalls in the Americas and in the basic track types (straight running or recurving). The formation sites with respect to the subtropical ridge were used to estimate to what extent formation site differences might have contributed to track differences. We used the 500 hPa height and wind anomalies to determine how anomalous steering flows might have affected the tracks, assuming that the 500 hPa winds give a good estimate of the steering flow for moderate and strong TCs. The 500 and 200 hPa height anomalies were used to determine the global scale origins of the steering flow anomalies.

1. July-August-September (JAS)

Fig. 17 shows that in JAS there were fewer (more) TC tracks during EN (LN) in the tropical NATL, Caribbean, and Gulf of Mexico. The differences in the tropical NATL were probably due mainly to the larger number of formations that occurred in the TATL and WAF regions during LN. However, the clear differences in the Caribbean and Gulf of Mexico suggest that TCs that did form in the tropics were less (more) likely to maintain a westward track during the EN (LN) events. Fig. 17 also indicates that there was a tendency for the TCs that formed in the subtropics during the EN events to begin an eastward track soon after formation. That tendency is less apparent in the tracks during LN events. There is also an indication in Fig. 17 that there were fewer tracks making a close approach to eastern North America (especially the northeastern U.S. and southeastern Canada) during EN events. Finally, Fig. 17 reveals a major

consequence of these track differences: that there were far more landfalls during the LN events than the EN events.

a. Westernmost Longitudes Reached by Hurricanes

Fig. 18 displays the westernmost longitudes for hurricanes during JAS and confirms that more hurricanes approached or entered the Caribbean, Gulf of Mexico, and southeastern U.S. during LN events. Of the 38 hurricanes represented in this figure, 12 occurred during EN events and 26 during LN events. So hurricanes in this region were twice as common in the LN events as in the EN events. The westernmost longitude differences confirm that there was a higher tendency for straight running TCs during LN events than during EN events. This is because hurricanes that occur in this region tend to have tracked in from remote locations, and only get deep into the Caribbean and Gulf of Mexico if they maintain a straight running track. This not as true for less intense TCs, which often form in the Caribbean and Gulf. Thus, less intense TCs are not as useful as hurricanes in using differences in westernmost longitudes to determine track type differences. In addition, hurricane strength TCs are more relevant when considering landfall hazards.

b. TC Formation Sites and the Subtropical Ridge

Fig. 19 shows the TC formation sites and the 500 hPa heights during JAS. The highest heights, extending east-west at about 20-35°N, represent the subtropical ridge (STR), a major factor in determining TC steering flows. TCs that form equatorward of the STR axis tend to track to the west, under the influence of the easterly flow along the south flank of the ridge. TCs

that form poleward of the ridge axis tend to track eastward, under the influence of the midlatitude westerly flow along the north flank of the STR.

Fig. 19 shows that a higher percentage of the TC formations occurred equatorward of the STR during the LN events, with many of those formation occurring just east of the Caribbean. During the EN events, many of the TCs formed at or north of the STR axis. These results indicate that the formation sites with respect to the STR probably contributed to the greater tendency for TCs in JAS to track into the Caribbean, Gulf of Mexico, and eastern U.S. during the LN events (see Fig. 17). Fig. 19 also shows that during the LN events, the STR over the southern U.S., Gulf of Mexico, and western NATL was weaker and centered farther to the northeast than during the EN events. This difference in the strength of the STR might have been expected to have made straight running TCs more (less) likely during the EN (LN) events, had the formation sites and numbers been the same for the EN and LN events. That this was not the case indicates that the formation site differences were important in determining the track differences.

c. Anomalous 500 hPa Heights and Winds

Fig. 20 shows the EN and LN composite anomalous 500 hPa heights and winds during JAS. The patterns shown in Fig. 20 are similar to those at 700 hPa and 200 hPa, an indication that the anomalies were equivalent barotropic (see Chapter I). The anomalies were strongest at 200 hPa and weakest at 700 hPa. We focused on the 500hPa anomalies as a good representation of the anomalous steering flow for TCs with moderate to strong

intensities, but we got similar results when we examined the 700hPa and 200 hPa anomalies. The magnitudes of the wind anomalies near North America are relatively large at all levels. For example, east of North Carolina at about 70oW, the 500 hPa wind speed anomalies shown in Fig. 20 are about 15 percent of the actual wind speeds, and the EN-LN wind speed differences implied by Fig. 20 are about 30 percent of the actual wind speeds.

Fig. 20 shows that during the EN events, the anomalous 500 hPa winds were westward over most of the subtropical and midlatitude NATL, and over the western tropical NATL between about 18-25°N. The wind anomalies in the corresponding LN composite are nearly opposite over most of the tropical and subtropical NATL, and over the midlatitude northwestern Atlantic. The EN-LN differences in the wind anomalies are consistent with the track differences described at the beginning of section D.1, above. Thus, eastward wind anomalies tended to steer TCs away from the Caribbean, Gulf of Mexico, northeastern U.S., and southeastern Canada during the EN events, while westward wind anomalies tended to do the opposite during LN events.

d. TC tracks and Anomalous 500hPa Heights and Winds

The EN and LN composite tracks for JAS, along with the height and wind anomalies presented in Fig. 20, are shown in Fig. 21. This Fig. reinforces the results described in the preceding sections about how the tracks were related to the steering anomalies. Consider, for example, the northeastern U.S. and Canadian Maritime Provinces, where the climatological winds at 500 hPa are westerly during JAS (Palmen and Newton 1969). Fig. 21 shows that in this

region during the EN events, the 500 heights were unusually low and the westerlies unusually strong, and TCs tended to be steered away from the land. During the LN events, the heights were unusually high and the westerlies unusually weak, and TCs tended to be steered more onshore.

2. September-October-November (SON)

Fig. 22 shows the EN and LN composite tracks for SON, along with the 200 hPa height anomalies. The track differences are similar to those in JAS (Fig. 17), but even more pronounced. The track differences in and near the Gulf of Mexico and the eastern U.S. are especially striking, with far more tracks and landfalls in these regions during the LN events than during the EN events. The 200 hPa height anomalies in SON are also quite different, with a strong negative (positive) height anomaly over eastern North America and a strong positive (negative) height the western North Atlantic during the EN (LN) events. As discussed in Chapter 3, section C, these height anomalies are part of anomalous wave trains emanating from East Asia and the western tropical Pacific. Their impacts on TC tracks are discussed in the following sections.

a. Westernmost Longitudes Reached by Hurricanes

Fig. 23 displays the westernmost longitudes for hurricanes during SON and shows that far more hurricanes approached or entered the Caribbean, Gulf of Mexico, and southeastern U.S. during LN events. Of the 27 hurricanes represented in this figure, 8 occurred during EN events and 19 during LN events. So hurricanes in this region were more than twice as common in the LN events as in the EN events. As in the JAS case, the westernmost longitudes differences

indicate that there was a higher tendency for straight running TCs during LN events than during EN events.

b. TC Formation Sites and the Subtropical Ridge

Fig. 24 shows the TC formation sites and the 500 hPa heights during SON. Note that the STR is much weaker and further south than in JAS. The height anomalies in Figs. 22 and 25 indicate that the anomalous wave trains contribute to an anomalously strong (weak) STR during the EN (LN) events.

As in JAS, a higher percentage of the TC formations occurred equatorward of the STR during the LN events, with many of those formation occurring just east of the Caribbean (Fig. 24). During the EN events, many of the TCs formed at or north of the STR axis. So, as in JAS, the large number of formation sites equatorward of the STR probably contributed to the greater tendency during the LN events for TCs to track into the Caribbean, Gulf of Mexico, and eastern U.S. (see Fig. 22). It is also possible that the anomalously weak STR during the LN events contributed to the recurvature of some of the TCS that had formed in the tropical North Atlantic shown in Figs. 22 and 25.

c. Anomalous 500hPa Heights and Winds

Fig. 25 shows the EN and LN composite anomalous 500 hPa heights and winds during SON. As in JAS, the patterns shown in Fig. 25 are similar to those at 700 hPa and 200 hPa, with the strongest anomalies at 200 hPa and the weakest at 700 hPa. The magnitudes of the wind anomalies near North America are relatively large at all levels. For example, east of North Carolina at about 70°W, the 500 hPa wind speed anomalies shown in Fig. 25 are

about 15 percent of the actual wind speeds, and the EN-LN wind speed differences implied by Fig. 25 are about 30 percent of the actual wind speeds.

Fig. 25, when compared with Figs. 16 and 22, shows the dramatic impacts of the anomalous wave trains on the steering. In both the EN and LN composites, the strong wind anomalies along and near the Gulf and east coasts of North America are a result of the strong height anomalies over North America and the western North Atlantic, which are themselves part of the anomalous wave trains. The opposite directions of the vector wind anomalies in these areas help explain the strong differences in tracks indicated in Figs. 22 and 23. Note in particular, that the anomalous winds near the Gulf and east coasts tended to steer TCs into (away from) the Gulf of Mexico and the eastern U.S. during the LN (EN) events.

d. TC tracks and Anomalous 500hPa Heights and Winds

The EN and LN composite tracks for SON, along with the height and wind anomalies presented in Fig. 25, are shown in Fig. 26. This Fig. reinforces the results described in the preceding sections about how the tracks were related to the steering anomalies created by the anomalous wave trains. Consider, for example, the Gulf of Mexico, where the climatological winds at 500 hPa are westerly during SON (Palmen and Newton 1969). Fig. 26 shows that north of this region during the LN events, the 500 heights were unusually high and the westerlies unusually weak, and TCs tended to be steered into the Gulf. During the EN events, the heights to the north of the Gulf were unusually low and

the westerlies unusually strong, and TCs tended to be steered away from the Gulf.

3. TC Tracks Summary

We found that during JAS and SON there were large differences in tropical cyclone tracks between the EN and LN events, especially in the Caribbean, Gulf of Mexico, and near the east coast of the U.S. The EN-LN track differences were due to: (1) differences in TC formation numbers and locations; and (2) anomalous steering flows that resulted from anomalous tropospheric heights. The track differences were especially large during SON, when the anomalous wave trains from East Asia and the western tropical Pacific were well developed over North America and the North Atlantic. The causes of the formation differences and the anomalous tropospheric heights are discussed in Chapter 3, section C. The track differences are important because they affect TC landfalls, which can cause extensive damage and loss of life.

IV. SUMMARY AND CONCLUSIONS

A. SUMMARY

We have studied the impacts of EN and LN events on TCs in the North Atlantic, and the mechanisms by which these impacts occur. A broad based multivariate index and objective selection method were used to identify the ten strongest EN and LN events during the North Atlantic TC season that occurred over the 30-year period, 1970-1999. We used these ten strongest events to create 10-year EN and LN composites of North Atlantic TC data and global scale NCEP reanalysis fields. These composites were analyzed at monthly and three-monthly scales to identify the EN-LN differences in: (1) North Atlantic TC activity; (2) the atmospheric and oceanic environment of the North Atlantic basin; and (3) the global scale circulation. The differences in the basin-scale environment were used to assess the factors that directly affected TC activity on a seasonal-mean basis. The global-scale differences in the global scale environment were used to determine the mechanisms by which EN and LN events in the tropical Pacific extended their influence into the North Atlantic.

B. IMPACTS ON NORTH ATLANTIC TCS

The following major differences between TC activity during EN and LN events were found:

1. There was more TC activity at all levels of TC intensity during LN events than during EN events. The LTM TC activity was intermediate between the activities during LN and EN events.

2. During the LN events there were approximately one-third more TCs of TD, TS, and H intensity, and two-thirds more TCs of MH intensity, than during the EN events.

3. TC during the LN events had a greater average intensity then during EN events. The LTM TC intensity was intermediate between the intensities during the LN and EN events.

4. During the LN events, most TCs formed in tropical regions of the NATL. During the EN events, a high percentage formed in the subtropical NATL.

5. Vertical wind shear differences between the EN and LN events were a factor in explaining TC formations throughout the NATL.

6. SSTAs were a factor in explaining TC formation differences in the subtropical North Atlantic and central tropical North Atlantic.

7. OLR anomalies were a factor in explaining TC formation differences near west Africa and in the western Caribbean.

8. During the LN events, many more TCs approached or entered the Caribbean, Gulf of Mexico, and eastern U.S. regions than during the EN events. This led to many more landfalls during the LN events.

C. THE MECHANISMS OF EN AND LN IMPACTS ON TCS

A major goal of this study was to explore the mechanisms behind the impacts listed above. A number of mechanisms were identified through an

examination of the large-scale circulation changes that occurred during the EN and LN events. We concluded that a major way in which EN and LN events alter TC formation sites and tracks is by setting up anomalous quasi-stationary atmospheric waves that alter circulation patterns over large regions of the tropics and extratropics, and through the entire depth of the troposphere. These circulation changes alter the North Atlantic environmental factors that determine TC activity, especially vertical shear and steering flow.

During EN (LN) events, anomalous tropospheric warming (cooling) in the equatorial Pacific produces an anomalous equatorial Rossby-Kelvin wave response that creates anomalous upper level flow patterns throughout the tropics. These circulation anomalies produce anomalous upper level westerlies (easterlies) over northern Africa and the tropical North Atlantic during EN (LN) events. These wind anomalies increase (reduce) the vertical shear over most of the tropical North Atlantic basin during EN (LN) events. At the same time, anomalous tropospheric warming (cooling) in the western tropical Pacific during EN (LN) events triggers an anomalous extratropical wave train that extends eastward from East Asia and the western tropical Pacific into North America and the North Atlantic. This reduces (increases) the vertical shear in the subtropical North Atlantic during EN (LN) events. The anomalous circulations in the tropical and subtropical North American - North Atlantic region also alter the steering flow near the Gulf of Mexico and the eastern U.S. These steering changes tend to steer TCs away from (into) these regions during EN (LN) events.

A simple chain of events that summarizes the major mechanisms we have identified is listed below.

1. Large-scale circulation changes lead to changes in vertical shear and steering flow.
2. Vertical shear changes alter the number of formations and formation sites.
3. Changes in vertical shear and formation sites alter intensities.
4. Changes in vertical shear, formation sites, intensities, and steering flow alter TC tracks.
5. Changes in tracks alter intensities and landfalls.

D. CONTRIBUTIONS OF THIS STUDY

Numerous prior studies have been conducted on the impacts of EN and LN events on NATL TCs. Our study has confirmed findings from some of these studies, and developed a number of new findings about impacts and impact mechanisms. Many aspects of this study are unique. For example, unlike many past studies, we:

1. examined TC activity during ten EN events and ten LN events that occurred over 30 years, rather than a few events that occurred over a few years
2. examined EN and LN events, rather than just EN events, as in many past studies

3. used a Pacific-wide, multivariate index to identify EN and LN, rather than a regional and/or single-variable index

4. based our selection of EN and LN events on the intensity of the events during the NATL TC season, rather than on the peak intensities that general occur after the TC season

5. focused on events that occurred when extensive satellite observations were being made

6. examined a number of strong events from the late 1980s and 1990s that had not occurred when many past studies were conducted

7. used global reanalysis fields that were not available for many past studies

8. used compositing techniques to estimate characteristic patterns during EN and LN events, rather than using case studies

9. examined intra-basin and intra-season differences in TC activity, rather than just basin-wide and seasonal average differences

10. investigated EN and LN impacts on many aspects of TC activity (e.g., numbers of TC formations, TC intensities, formation sites, tracks)

11. studied differences in several basin scale environmental factors that affect TC activity (e.g., vertical shear, SST, deep

convection, winds and relative vorticity throughout the troposphere)

12. examined the global scale features that accompanied the variations in NATL TC activity, rather than focusing just on NATL features

13. examined the mechanisms by which EN and LN events alter NATL TC activity, rather than just the statistical relationships between EN and LN events and NATL TC activity

These unique approaches allow this study to make a number of contributions to the understanding of how TC activity in the North Atlantic is altered by EN and LN events. Although some of the results from this study are similar to those from prior studies, the unique combination of data and methods used in this study make these results much more substantial than was possible from the prior studies alone. In addition, many of the results of this study are new, especially those concerning: (1) the intra-basin and intra-seasonal variations in EN and LN impacts; and (2) the basin scale and global scale mechanisms by which TC activity in the North Atlantic is altered during EN and LN events.

E. FUTURE FORECASTING APPLICATIONS

We have used low frequency, global scale processes to help explain synoptic-scale TC activity within a basin. We think this perspective and our results can be useful to TC forecasters and emergency management planners.

However, we doubt that forecasters and managers can take the results of this study and directly apply them on a daily basis.

We do think though that the characteristic patterns identified in this study could, with further study, become useful guides for what to monitor and anticipate on weekly and longer time scales. For example, monitoring and forecasting convective events in the western tropical Pacific could be useful in making NATL forecasts, since these events can trigger a wave train response that alters shear and steering in the NATL about five to 15 days after the event has started. Thus global scale forecasts focused on the NATL might be used by to make medium and longer range forecasts of synoptic activity in the NATL basin. For example, TC forecasters might use medium range forecasts of wave train developments to alter track forecasts for the Gulf of Mexico and eastern U.S. For the U.S. Navy, increased accuracy in TC formation and track forecasts near the Gulf and east coasts could save millions of dollars; for example, dollars spent on the unnecessary sorties of ships and aircraft, or on damage caused to ships and aircraft when necessary sorties were *not* conducted.

F. RECOMMENDATIONS FOR FURTHER RESEARCH

In this study we have applied several new approaches to understanding the impacts of EN and LN events on NATL TC activity. These approaches are relatively simple and inexpensive, and we recommend that they be considered for use future studies. Our specific recommendations are listed below.

1. We recommend that investigation of the global scale mechanisms that cause differences in TC activity continue to be a focus of future studies on NATL TC activity.

2. This study applied a composite perspective to these mechanisms. But there is considerable variability in the evolution of individual EN and LN events. So further refinements of the event selection process would be useful, to reduce the differences between the events used in the composites.

3. It would be useful to conduct more detailed examinations of the temporal variations of TC activity within the five NATL regions we identified.

4. We conducted preliminary analyses of NATL TC activity during the ten years in 1970-1999 that we did not include in the EN and LN composites. These years had their own characteristic features in TC activity that were intermediate between the features seen in the EN and LN years, and similar to but not the same as the LTM features. Since periods in which neither an EN or a LN event is occurring are common, additional investigations should be done to identify the basin and global scale processes that affect TC activity during these periods.

5. The global scale mechanisms identified in this study of how interannual events (EN and LN events) affect NATL TC activity

also operate on shorted and longer tine scales. For example, Madden-Julian oscillations (MJOs) in the tropical Indian and Pacific Oceans may trigger alterations of the TEJ and extratropical wave trains. Also, the large scale circulation over the tropical North Atlantic and northern Africa is linked to variations of the Asian monsoon. Monsoon variations are themselves tied to EN and LN processes, but much of this variability is independent of EN and LN events. Thus, the connections between NATL TC activity and additional climate fluctuations (e.g., MJOs, monsoon active break events, biennial and decadal variations of the Asian monsoon) should be studied further.

6. recommend that studies be conducted to investigate the potential for a global scale monitoring system to identify and predict the impacts of remote, large scale, and/or low frequency processes on TC activity. Preliminary studies in such an effort should investigate further the statistical and dynamical links between different variables, such as convection in the western tropical Pacific and winds over the Gulf of Mexico and western North Atlantic. The products from these studies might include indices of large scale circulation in the NATL, teleconnection indices, and models that can simulate the responses of the NATL to remote processes.

We hope that this study will stimulate future studies of how global scale circulation anomalies and teleconnections impact basin scale processes and TC activity within these basins. In particular, we hope this study will help improve our ability to provide useful TC forecasts on weekly and longer time scales by identifying the lower frequency and large scale factors that affect TC activity.

APPENDIX A – FIGURES

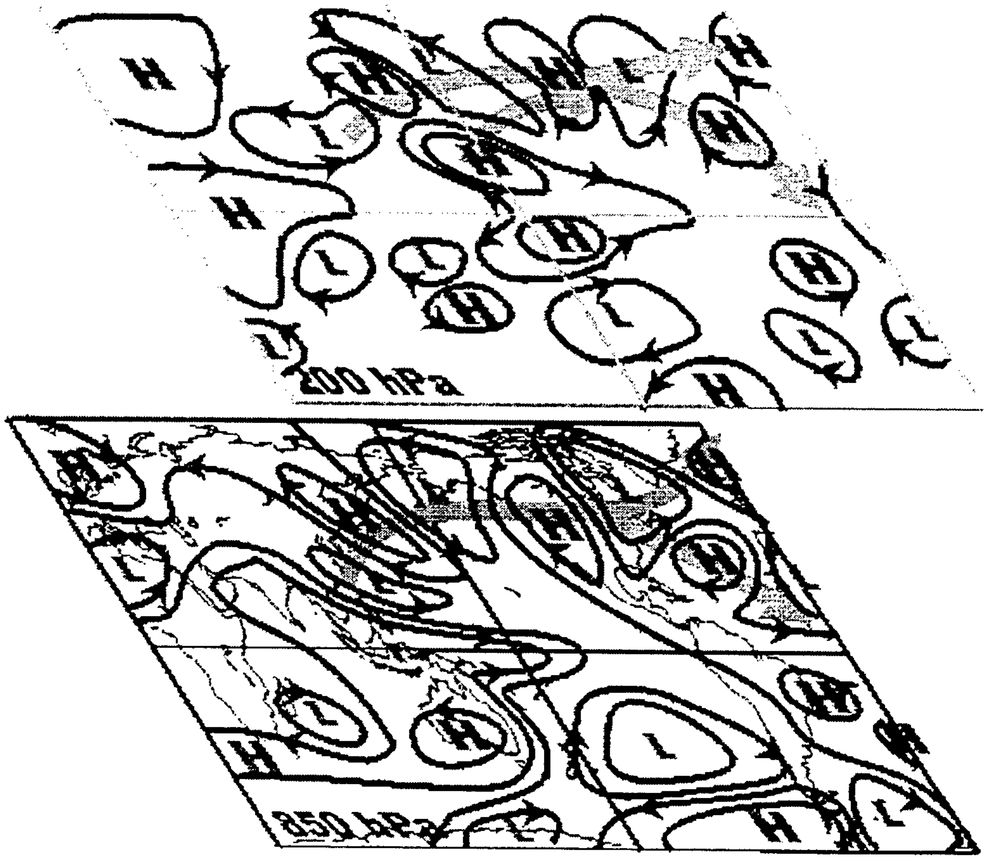

Figure 1. Schematic geopotential height anomalies at 850 hPa and 200 hPa during August-November of EN events. The alternating positive and negative height anomalies marked by the purple arrows indicate an equivalent barotropic wave train extending from East Asia to the North Atlantic. From Ford (2000).

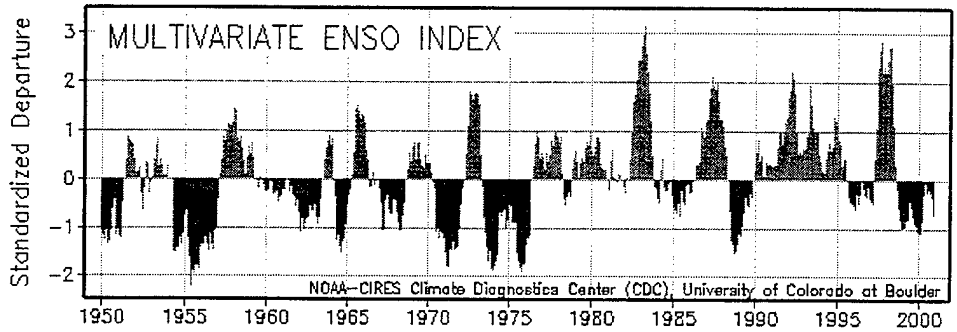

Fig. 2. MEI values for 1950-2000 showing EN (positive values, in red) and LN (negative values, in blue) events. From www.cdc.noaa.gov/~kew/MEI/mei.html. See Wolter and Timlin (1993) for more information on the MEI.

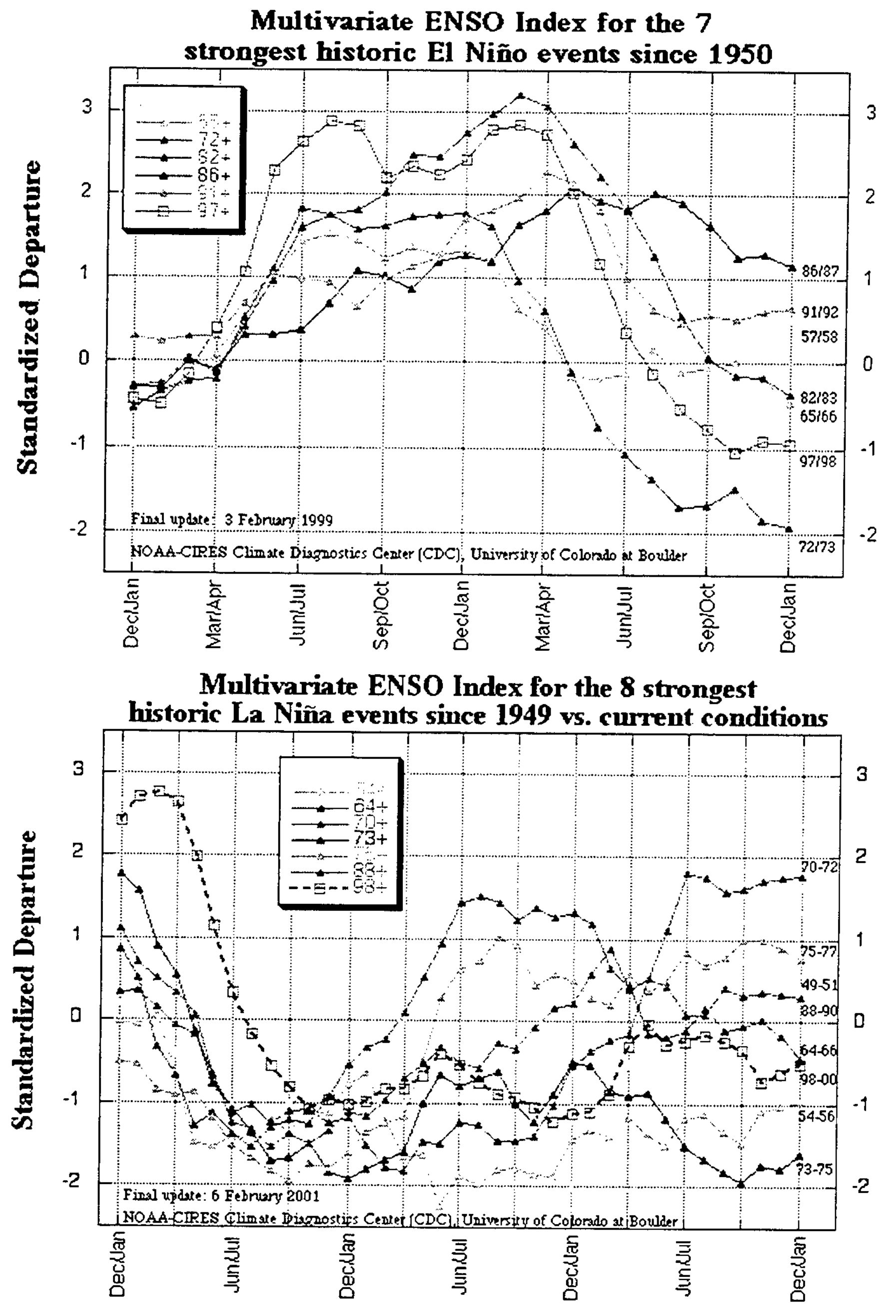

Figure 3. Evolution of EN and LN events depicted by the MEI. From www.cdc.noaa.gov/~kew/MEI/mei.html. See Wolter and Timlin (1993) for more information.

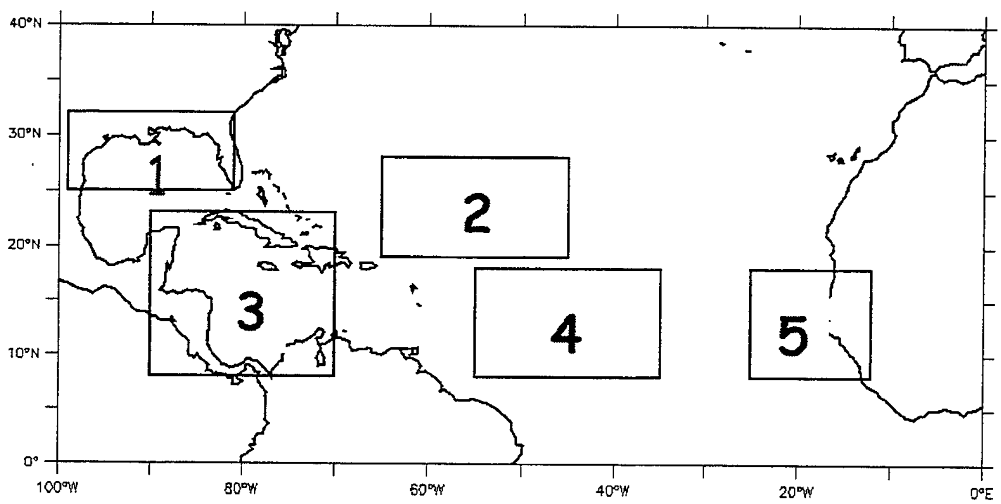

Figure 4. Regions used in this study to highlight differences in TC formation during EN and LN events. 1. Gulf of Mexico (GOMEX); 2. subtropical Atlantic (SATL); 3. western Caribbean (WCAR); 4. central tropical Atlantic (TATL); and 5. west Africa (WAF).

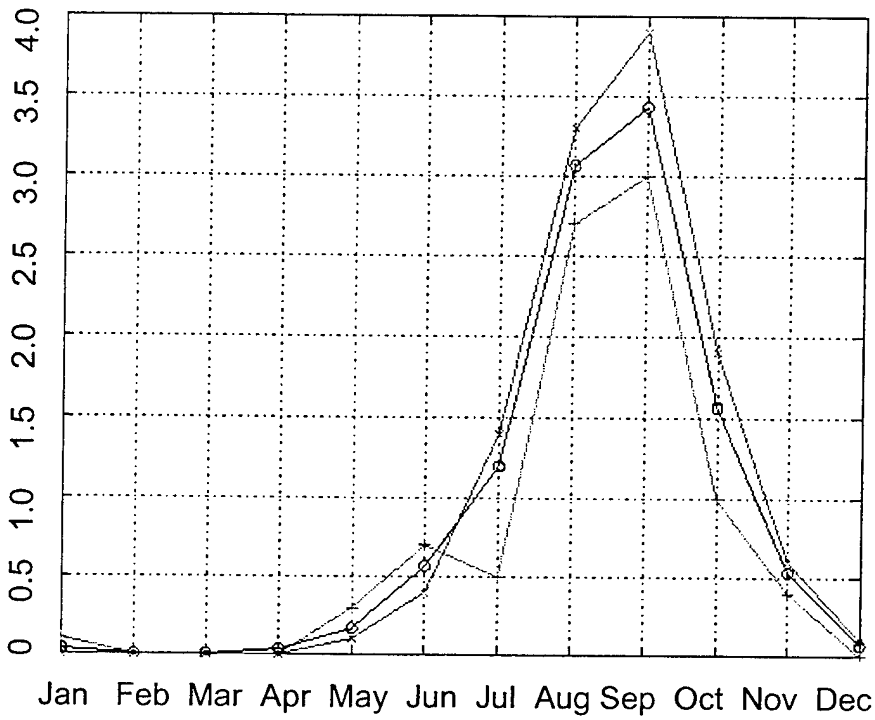

Figure 5. Monthly average numbers of TCs with intensities > 25 knots for EN (red) and LN (blue) events, and for the long term mean LTM (black).

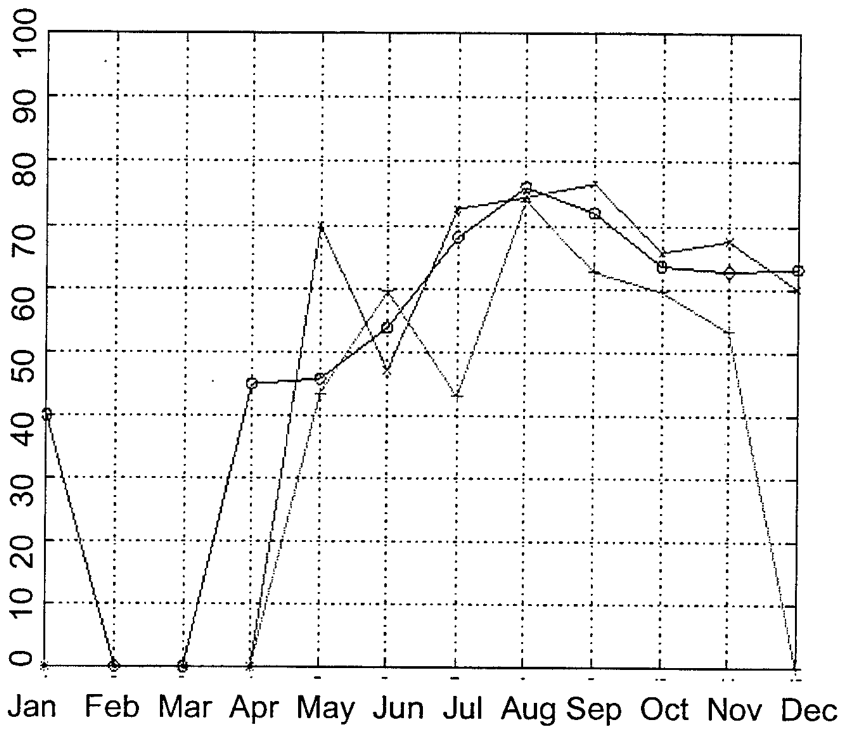

Figure 6. Monthly average TC intensity in knots for EN (red) and LN (blue) events, and for the LTM (black).

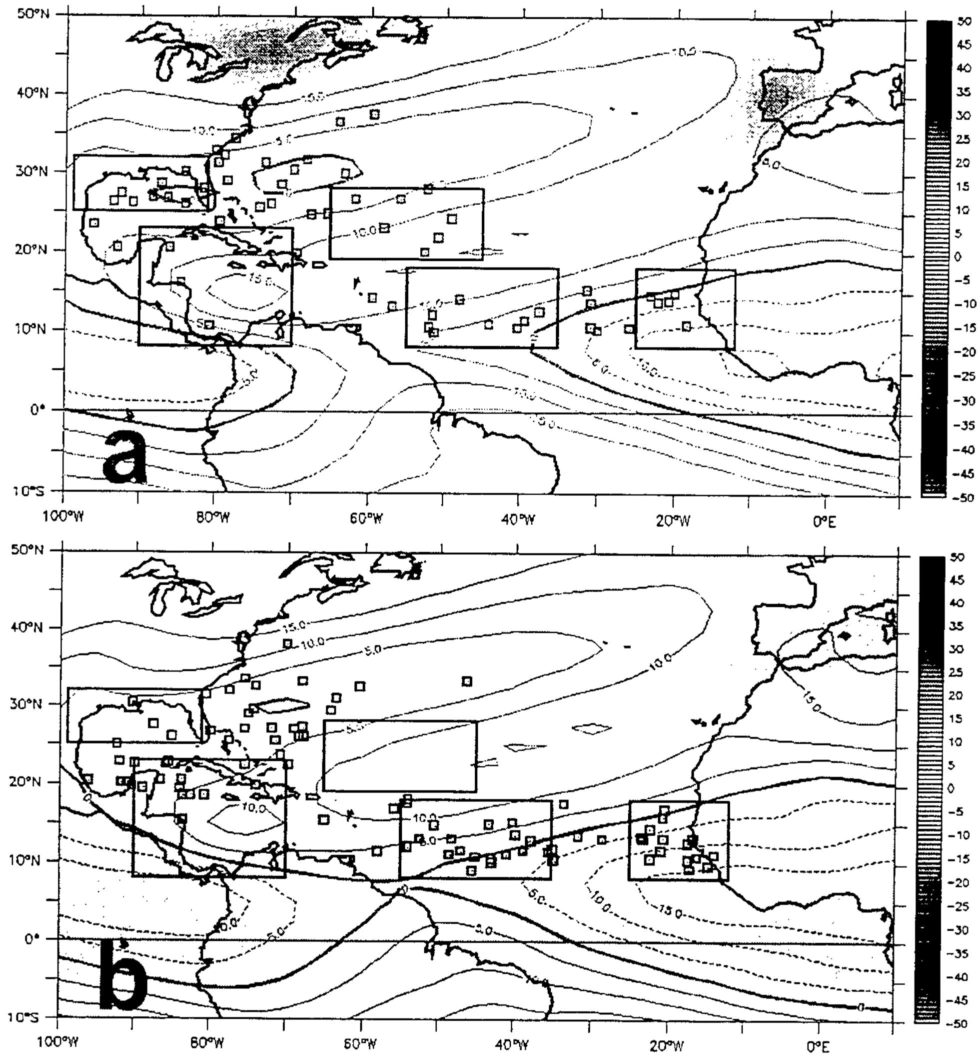

Figure 7. TC formation sites, vertical shear (U_{200}-U_{850}), and 200 hPa geopotential height anomalies during JAS. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Vertical shear is contoured at 5m/s intervals with the zero contour in bold. Height anomaly color scale is to the right of figures.

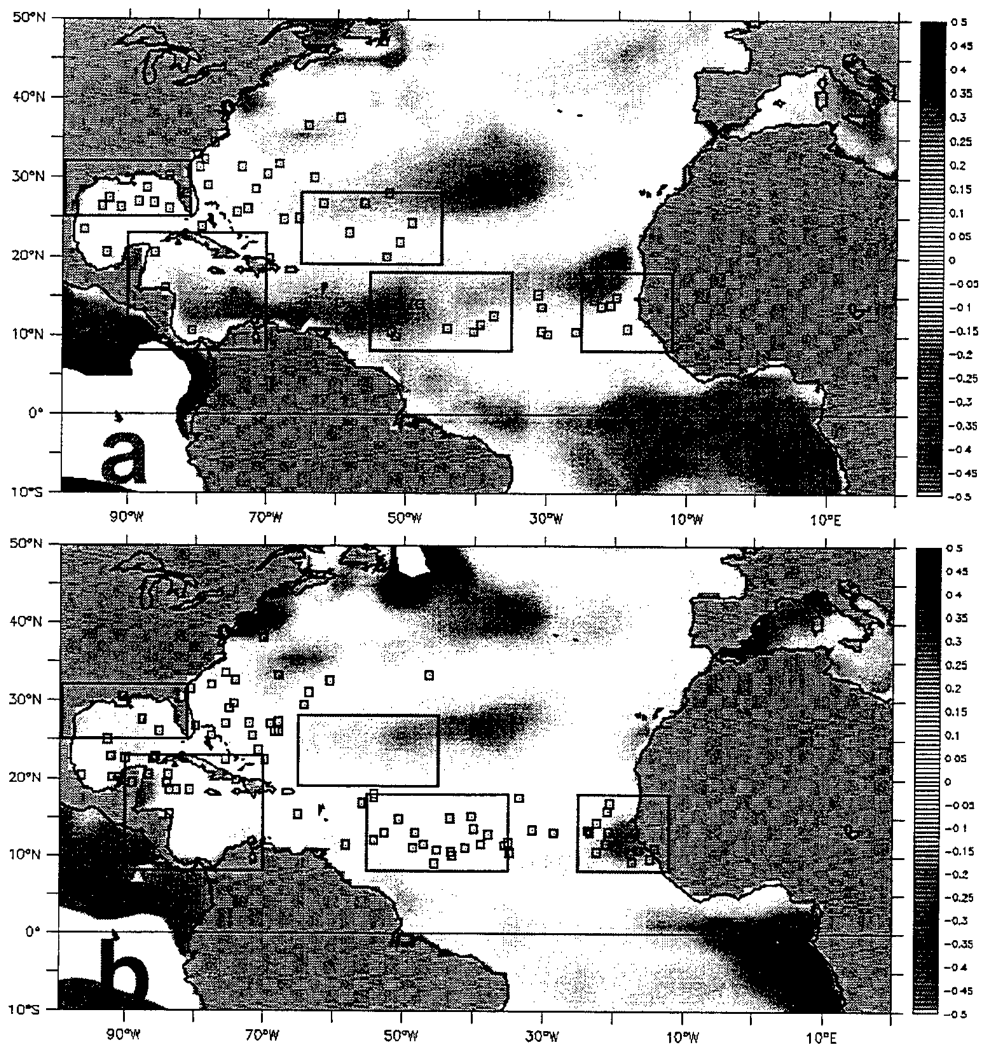

Figure 8. TC formation sites and SST anomalies during JAS. (a) El Niño; (b) La Niña. Formation sites are shown by squares. SST anomaly color scale is to the right of figures.

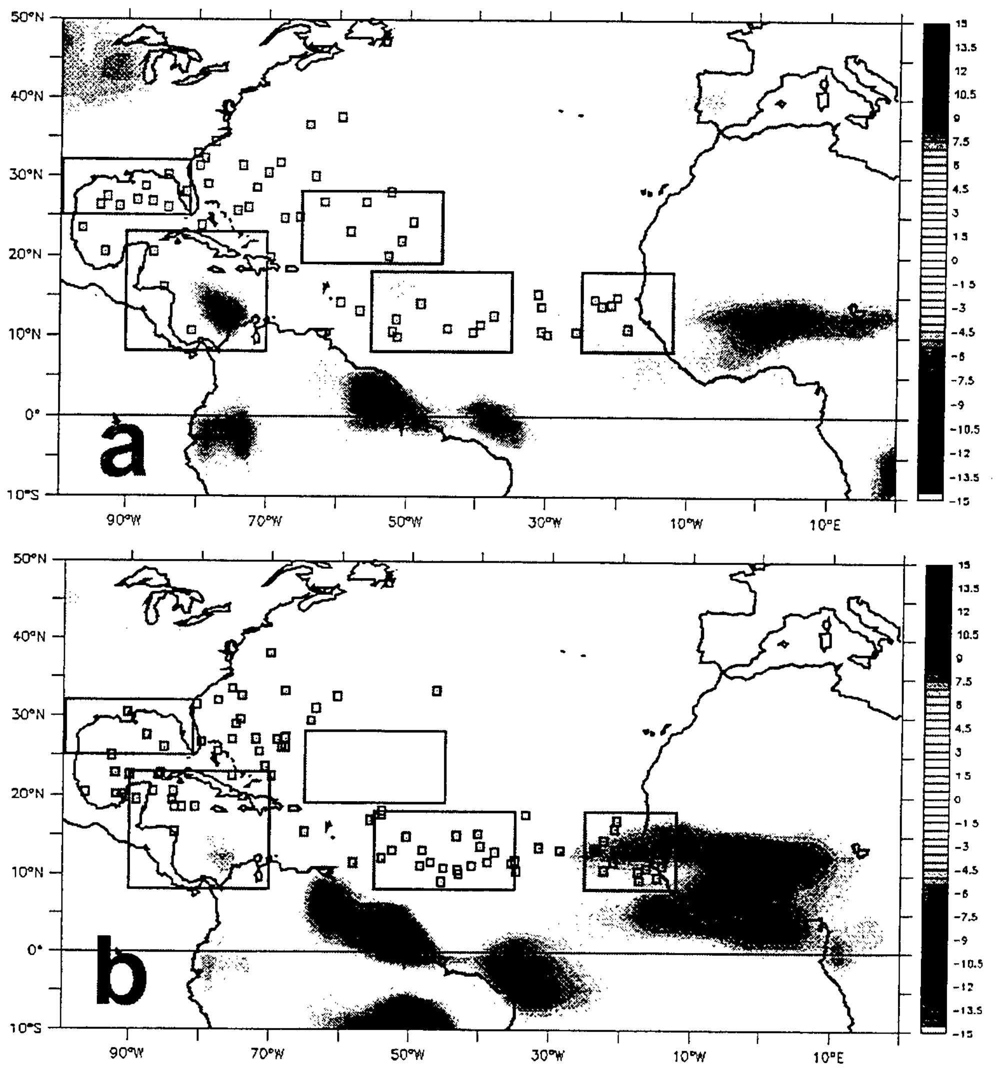

Figure 9. TC formation sites and OLR anomalies during JAS. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Negative (Positive) OLR anomalies represent anomalously strong (weak) convection. OLR anomaly color scale is to the right of figures.

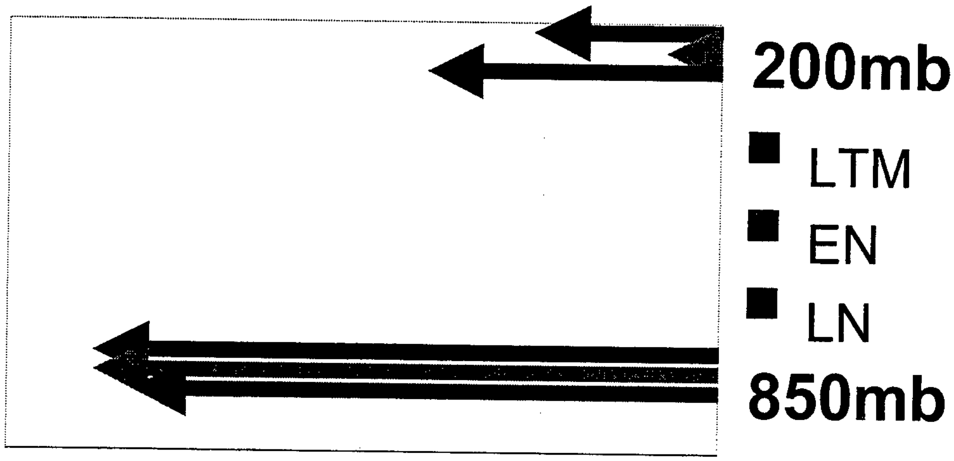

Figure 10. Zonal winds at 200 hPa and 850 hPa in the central tropical North Atlantic (TATL) region during JAS for EN (red) and LN (blue) events, and the LTM (black). The biggest EN-LN difference in zonal winds occurs at the 200 hPa level.

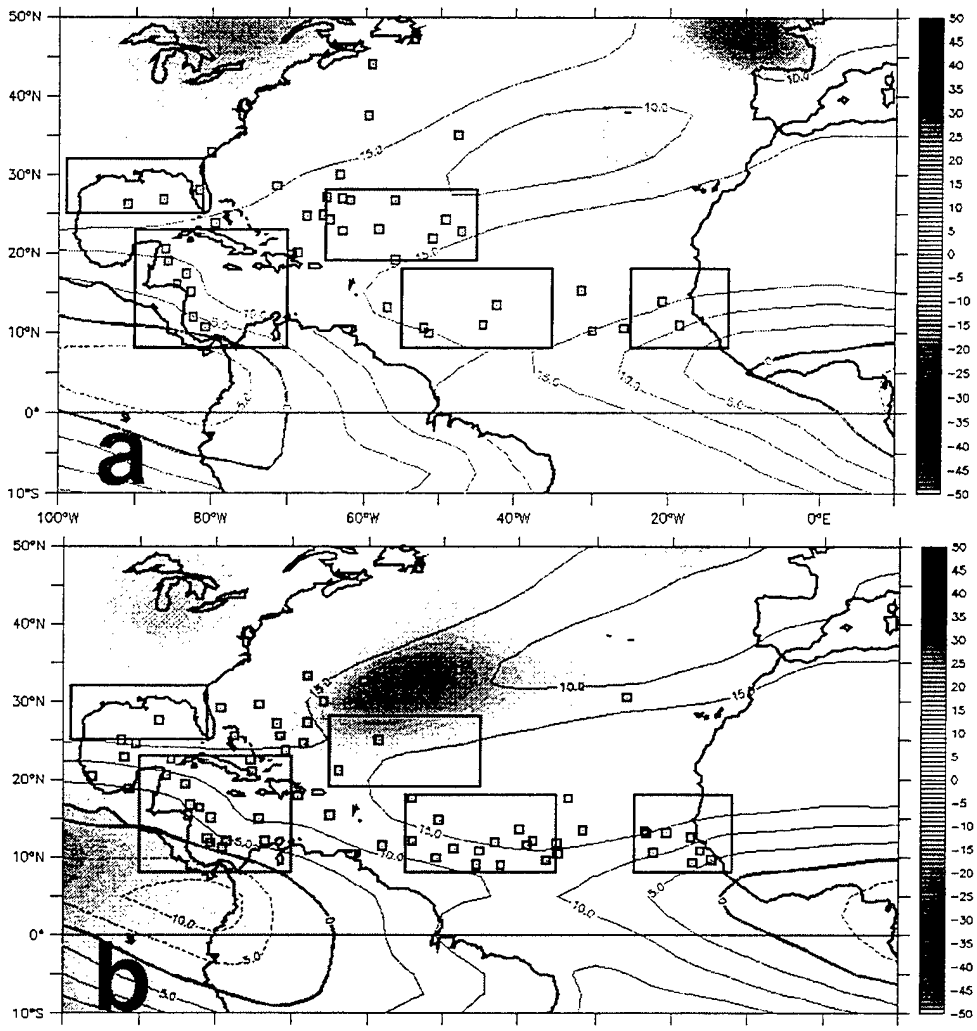

Figure 11. TC formation sites, vertical shear (U_{200}-U_{850}), and 200 hPa geopotential height anomalies during SON. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Vertical shear is contoured at 5m/s intervals with the zero contour in bold. Height anomaly color scale is to the right of figures.

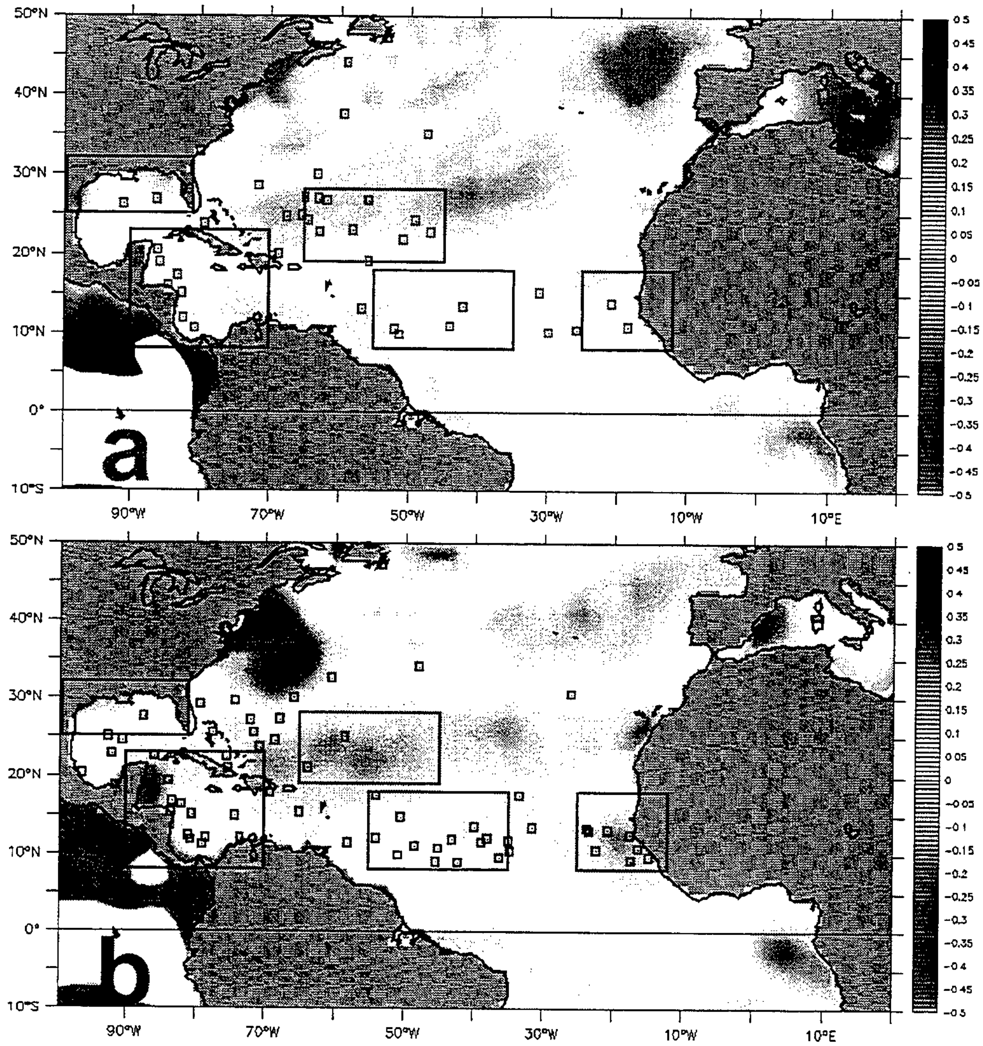

Figure 12. TC formation sites and SST anomalies during SON. (a) El Niño; (b) La Niña. Formation sites are shown by squares. SST anomaly color scale is to the right of figures.

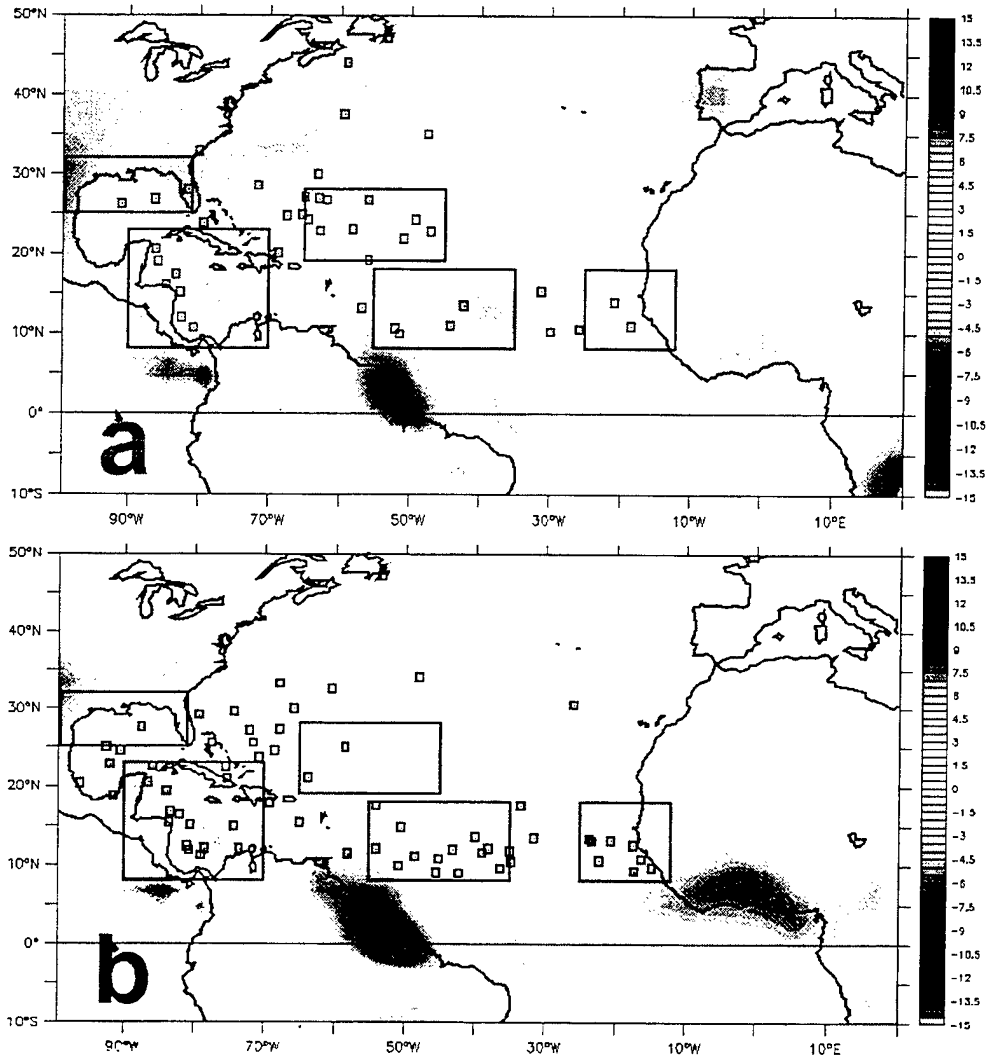

Figure 13. TC formation sites and OLR anomalies during SON. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Negative (Positive) OLR anomalies represent anomalously strong (weak) convection. OLR anomaly color scale is to the right of figures.

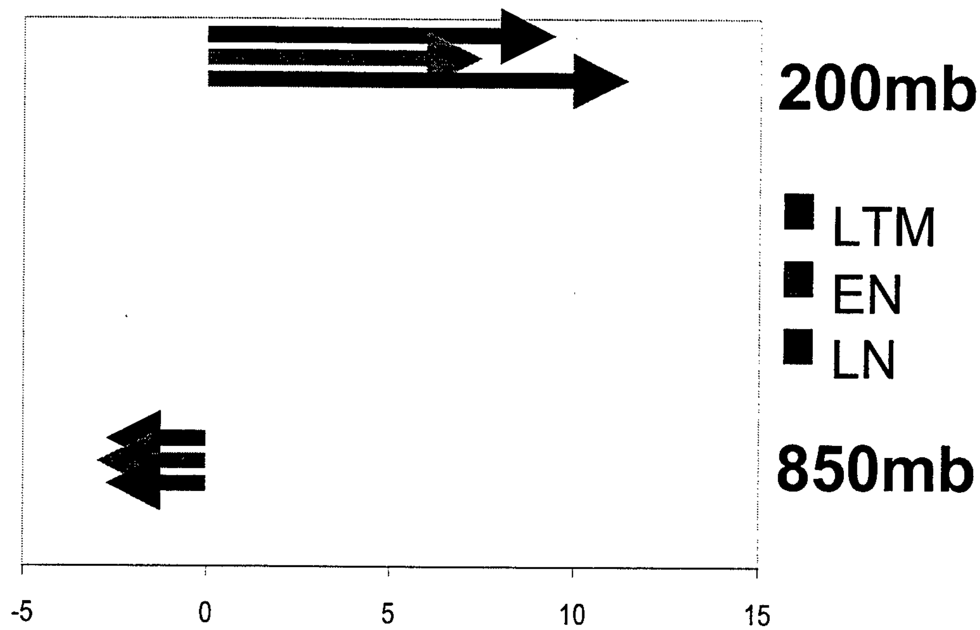

Figure 14. Zonal winds at 200 hPa and 850 hPa in the subtropical North Atlantic (SATL) region during SON for EN (red) and LN (blue) events, and the LTM (black). The biggest EN-LN difference in zonal winds occurs at the 200 hPa level.

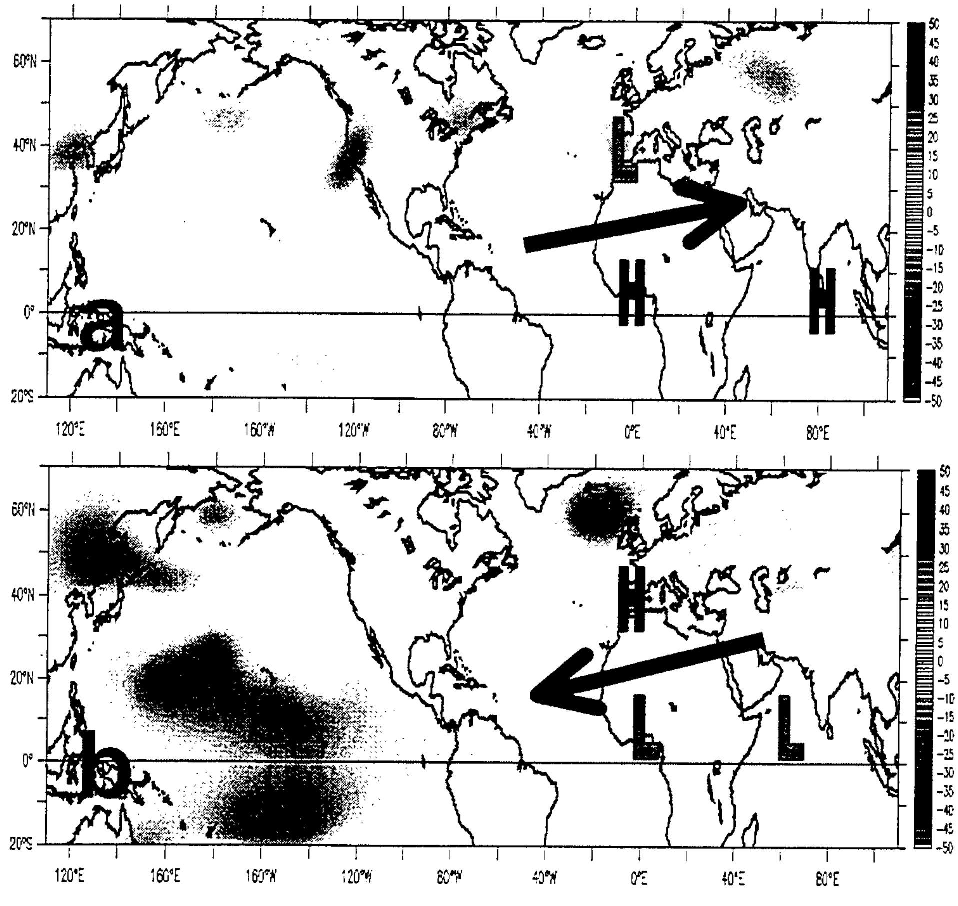

Figure 15. 200 hPa geopotential height anomalies during JAS. (a) El Niño; (b) La Niña. Hs and Ls highlight the 200 hPa height anomalies in selected regions. The solid arrows show schematically the 200 hPa wind anomalies in the tropical NATL, northern Africa, and southern Asia. Height anomaly color scale is to the right of figures.

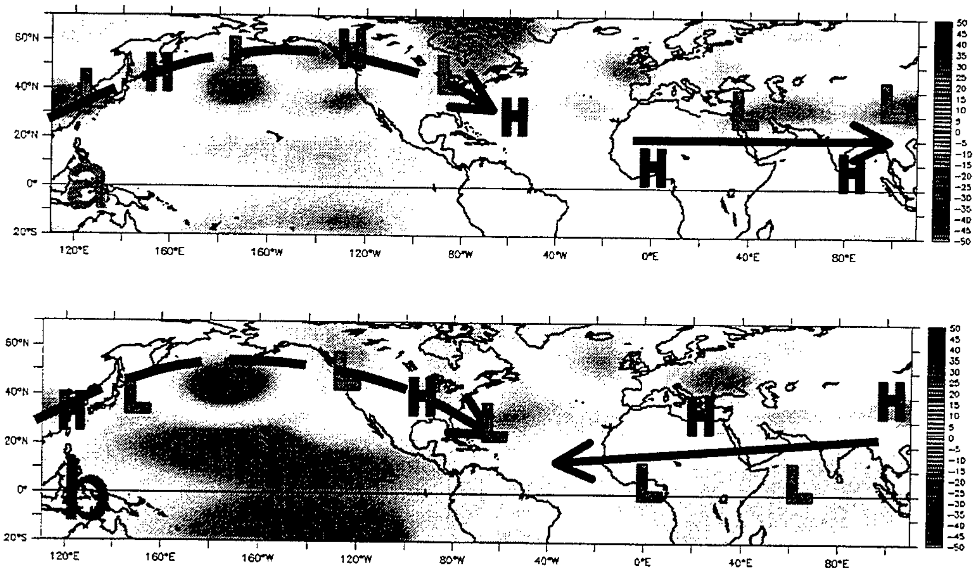

Figure 16. 200 hPa geopotential height anomalies during SON. (a) El Niño; (b) La Niña. Hs and Ls highlight the 200 hPa height anomalies in selected regions. The dashed arrows connecting the Hs and Ls in the East Asia-NATL region highlight the anomalous wave trains extending into the NATL region. The solid arrows show schematically the 200 hPa wind anomalies in the tropical NATL, northern Africa, and southern Asia. Height anomaly color scale is to the right of figures.

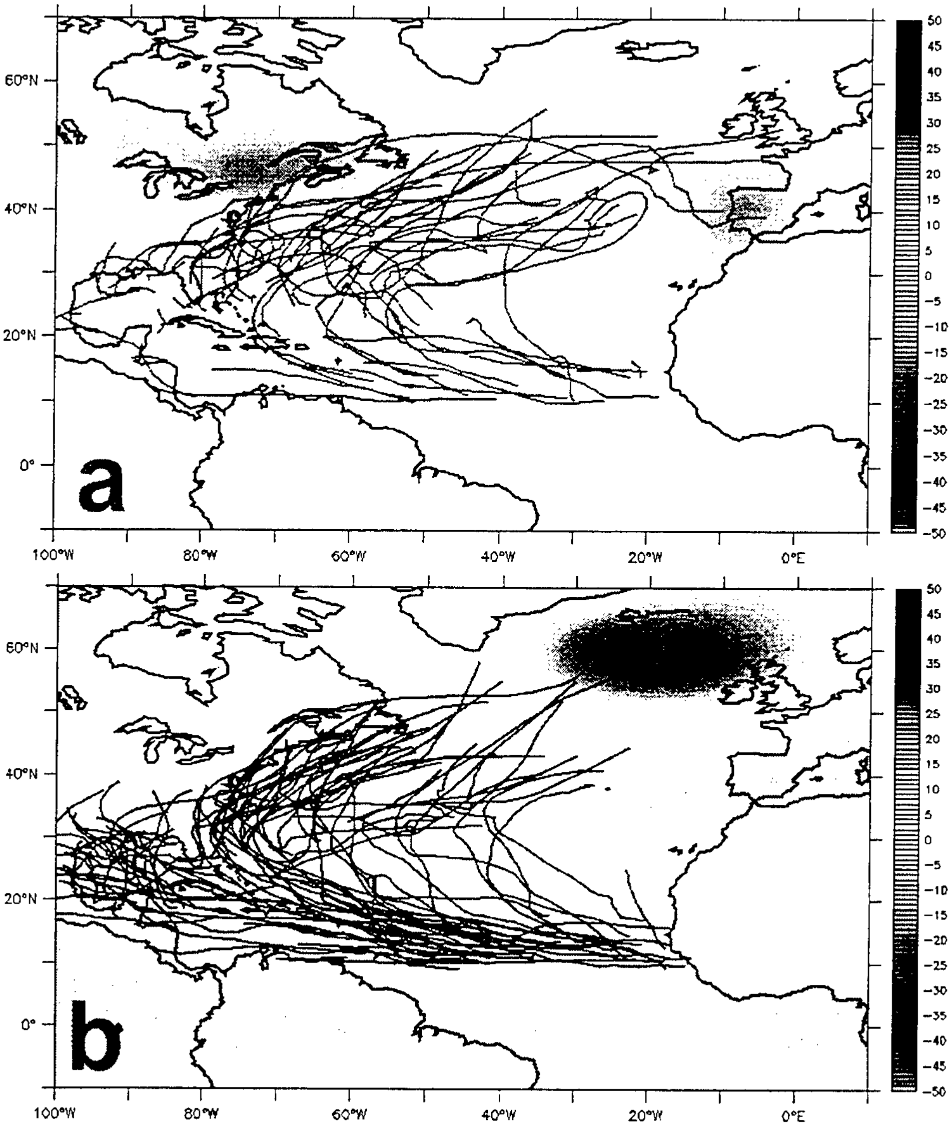

Figure 17. TC tracks and 200 hPa geopotential height anomalies during JAS. (a) El Niño; (b) La Niña. Height anomaly color scale is to the right of figures. Note that: EN (LN) events have fewer (more) tracks in the Gulf of Mexico and Caribbean regions; and EN (LN) events have fewer (more) westward tracking TCs.

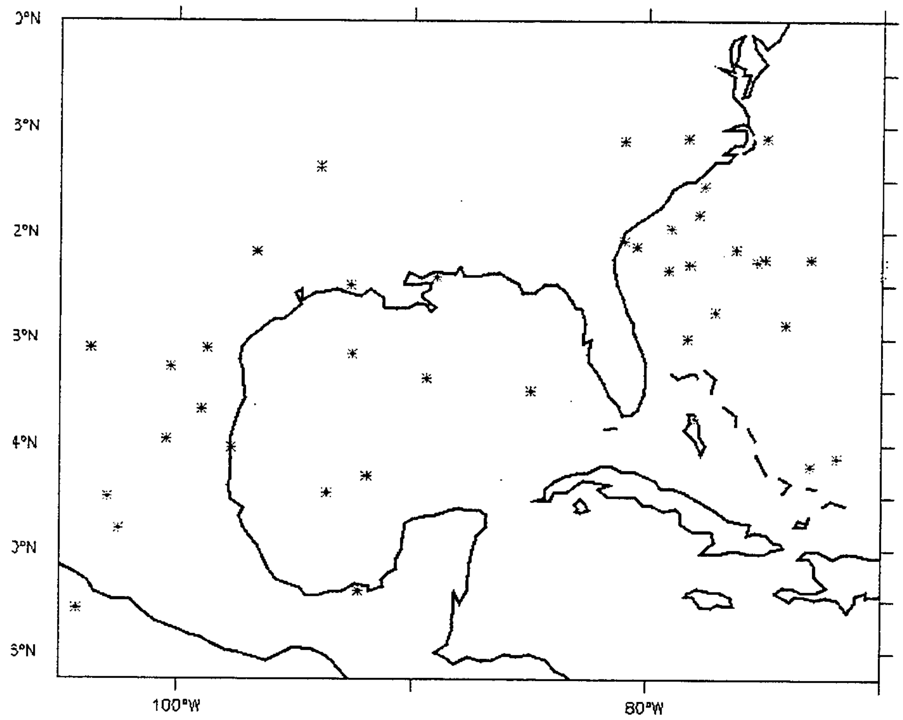

Figure 18. Westernmost longitudes that were reached by hurricanes in JAS during EN (red) and LN (blue) events, for the region shown. During EN (LN) events, 12 (26) hurricanes approached or entered this region.

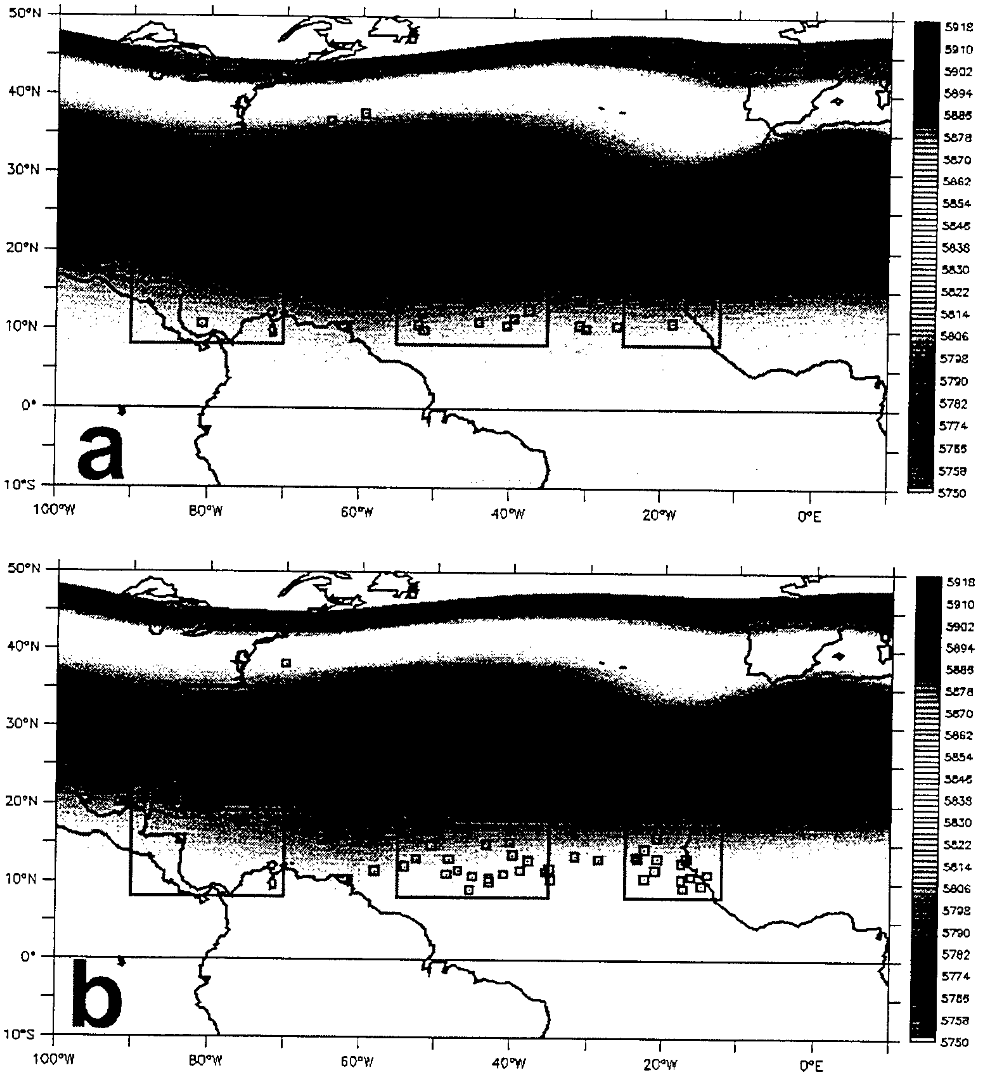

Figure 19. TC formation sites and 500 hPa geopotential height anomalies during JAS. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Height anomaly color scale is to the right of figures.

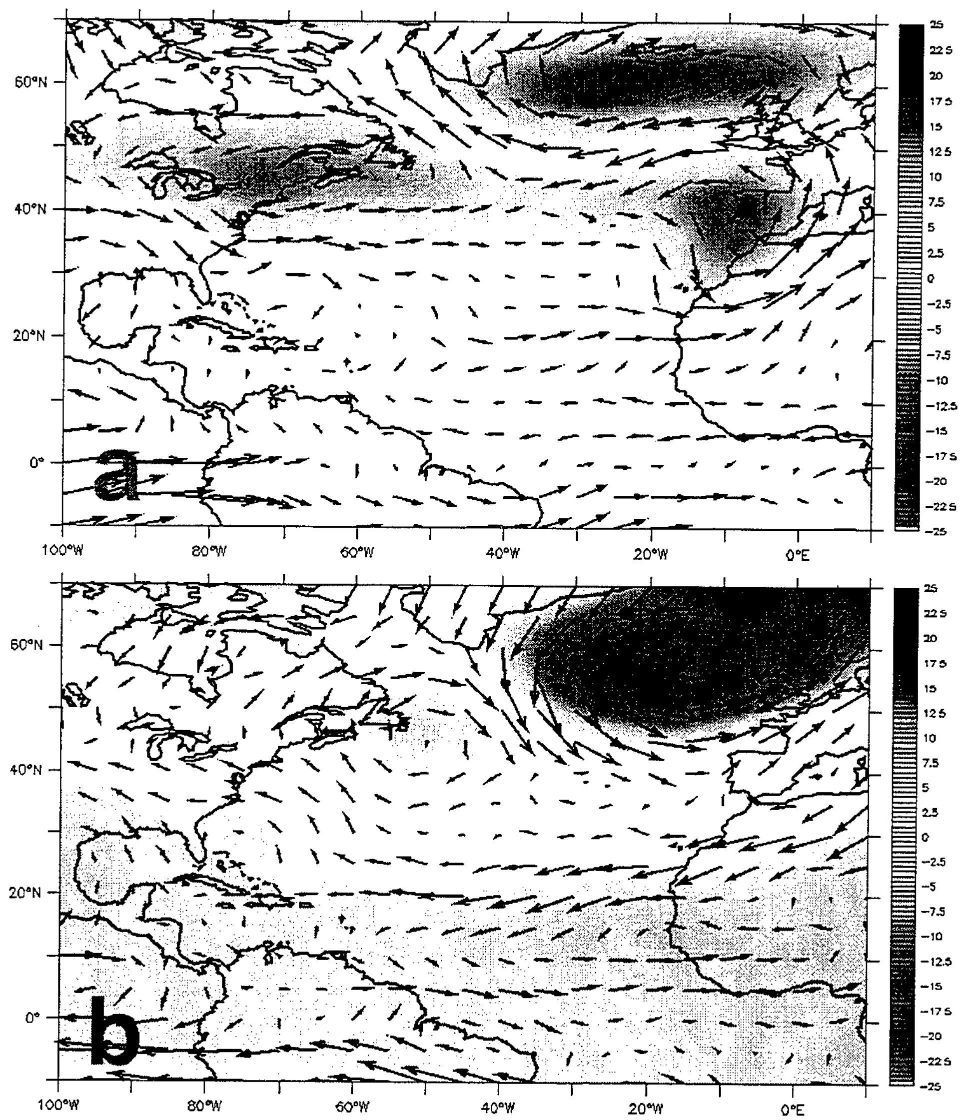

Figure 20. Anomalous 500 hPa geopotential heights and vector winds during JAS. (a) El Niño; (b) La Niña. Note the anomalous westerly (easterly) flow over much of the eastern U.S. during EN (LN) events. A vector five degrees long represents a wind speed of approximately 5 m/s. Height anomaly color scale is to the right of figures.

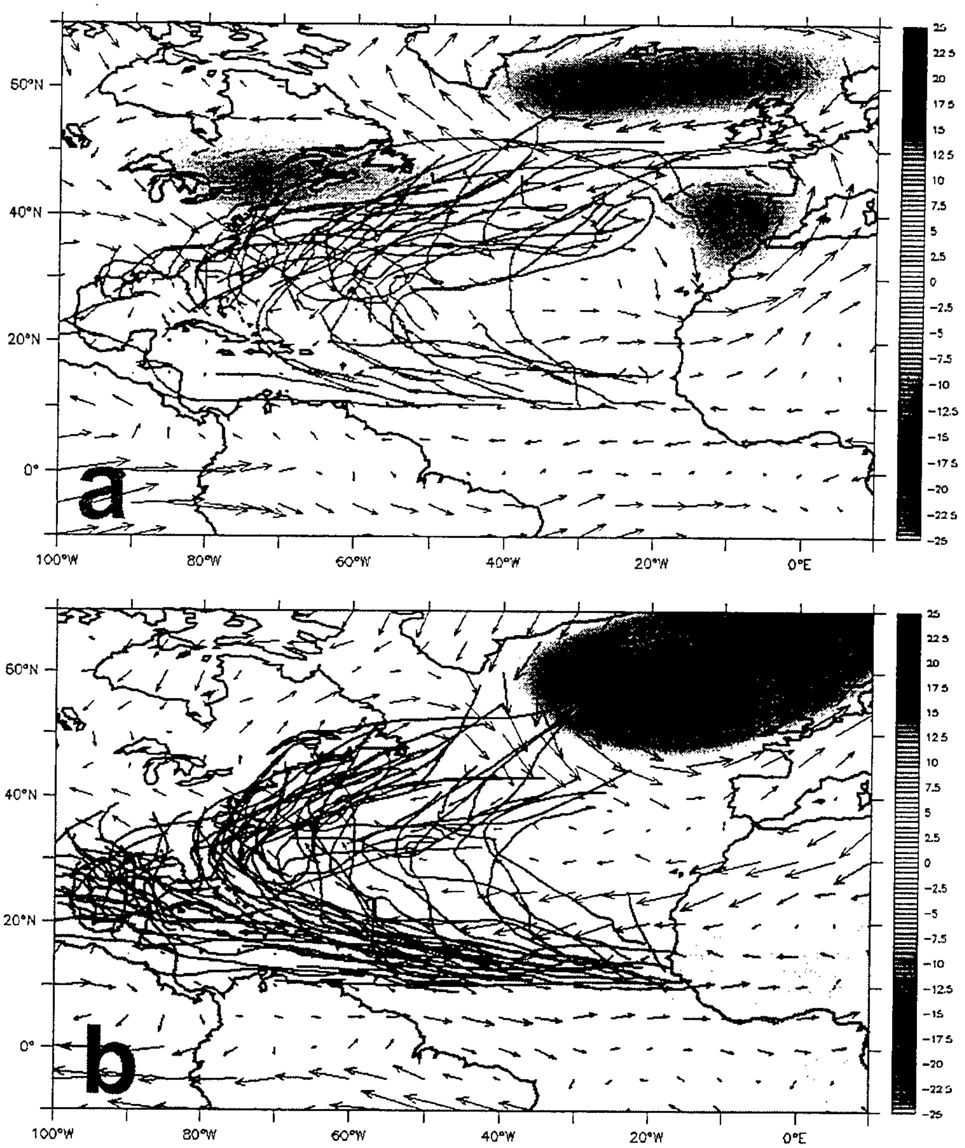

Figure 21. TC tracks and anomalous 500 hPa geopotential heights and winds during JAS. (a) El Niño; (b) La Niña. This figure contains the same information as Fig. 20, but with tracks added. The EN-LN differences in the tracks, and especially the differences in their proximity to U.S. coastal areas, is related to the differences in the steering flows implied by the anomalous 500 hPa winds (cf. Fig. 20). A vector five degrees long represents a wind speed of approximately 5 m/s. Height anomaly color scale is to the right of figures.

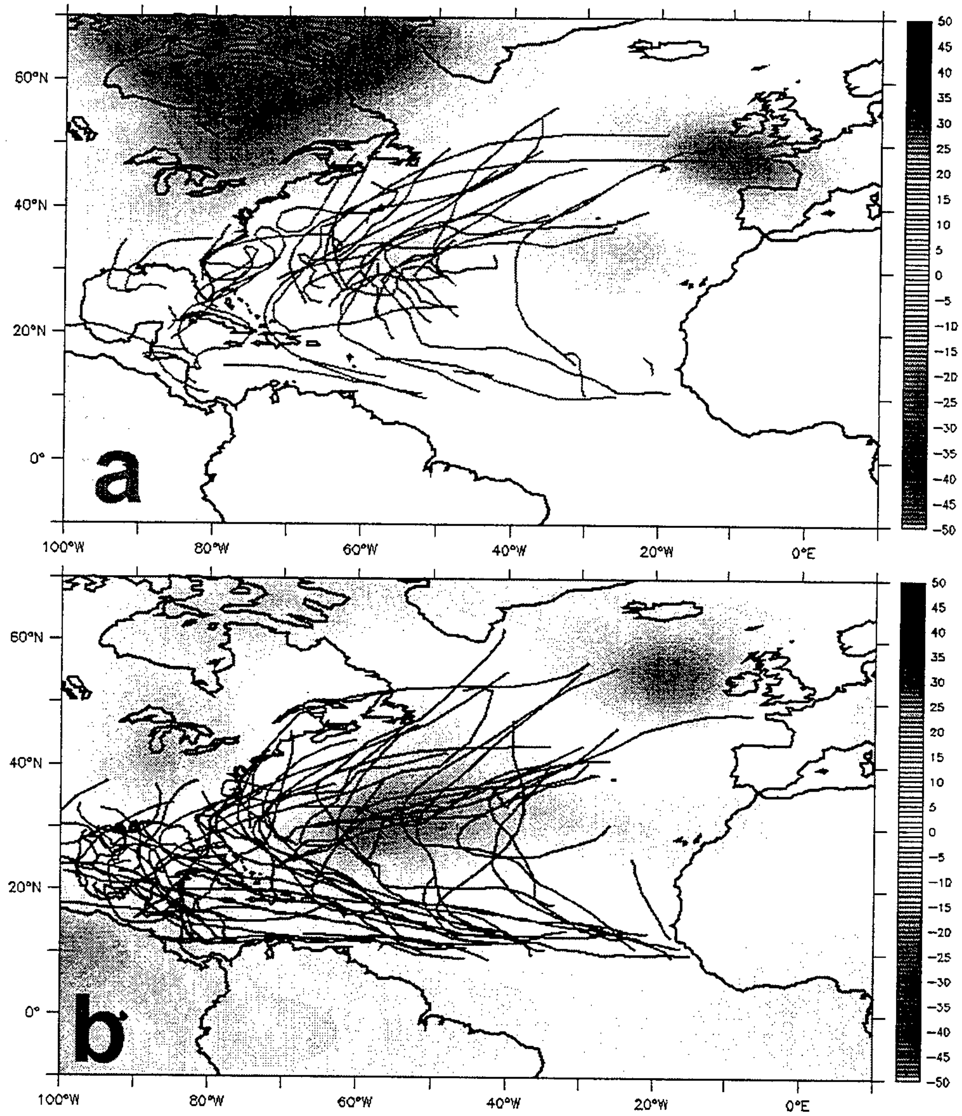

Figure 22. TC tracks and 200 hPa geopotential height anomalies during SON. (a) El Niño; (b) La Niña. Note that: EN (LN) events have fewer (more) tracks in the Gulf of Mexico and Caribbean regions; and EN (LN) events have fewer (more) westward tracking TCs. Height anomaly color scale is to the right of figures.

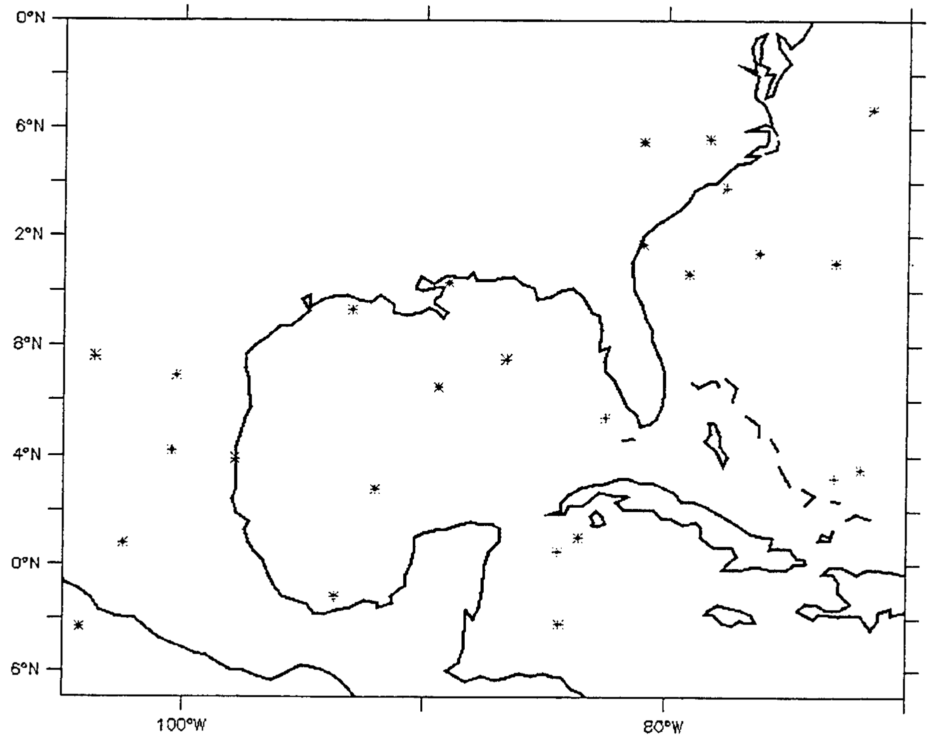

Figure 23. Westernmost longitudes that were reached by hurricanes in SON during EN (red) and LN (blue) events, for the region shown. During EN (LN) events, 8 (19) hurricanes approached or entered this region.

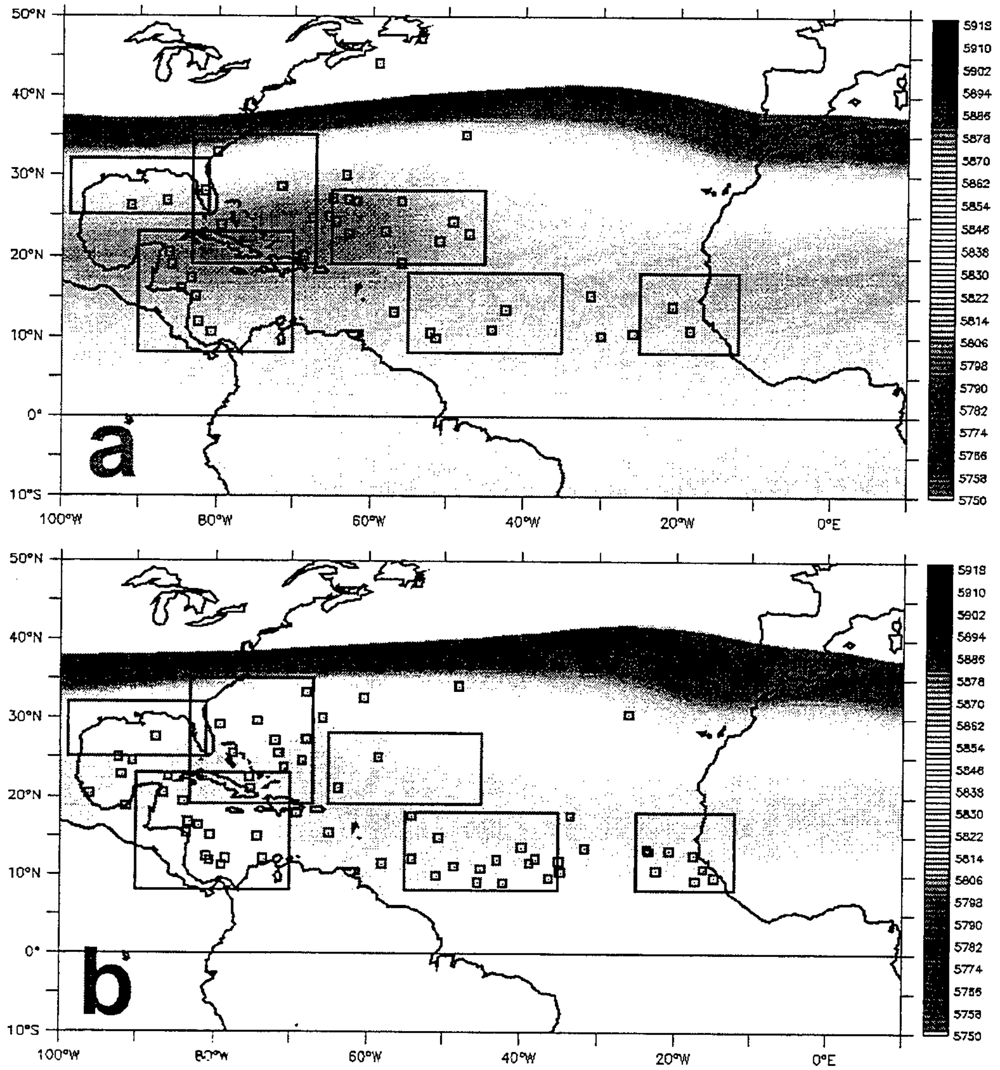

Figure 24. TC formation sites and 500 hPa geopotential height anomalies during SON. (a) El Niño; (b) La Niña. Formation sites are shown by squares. Height anomaly color scale is to the right of figures.

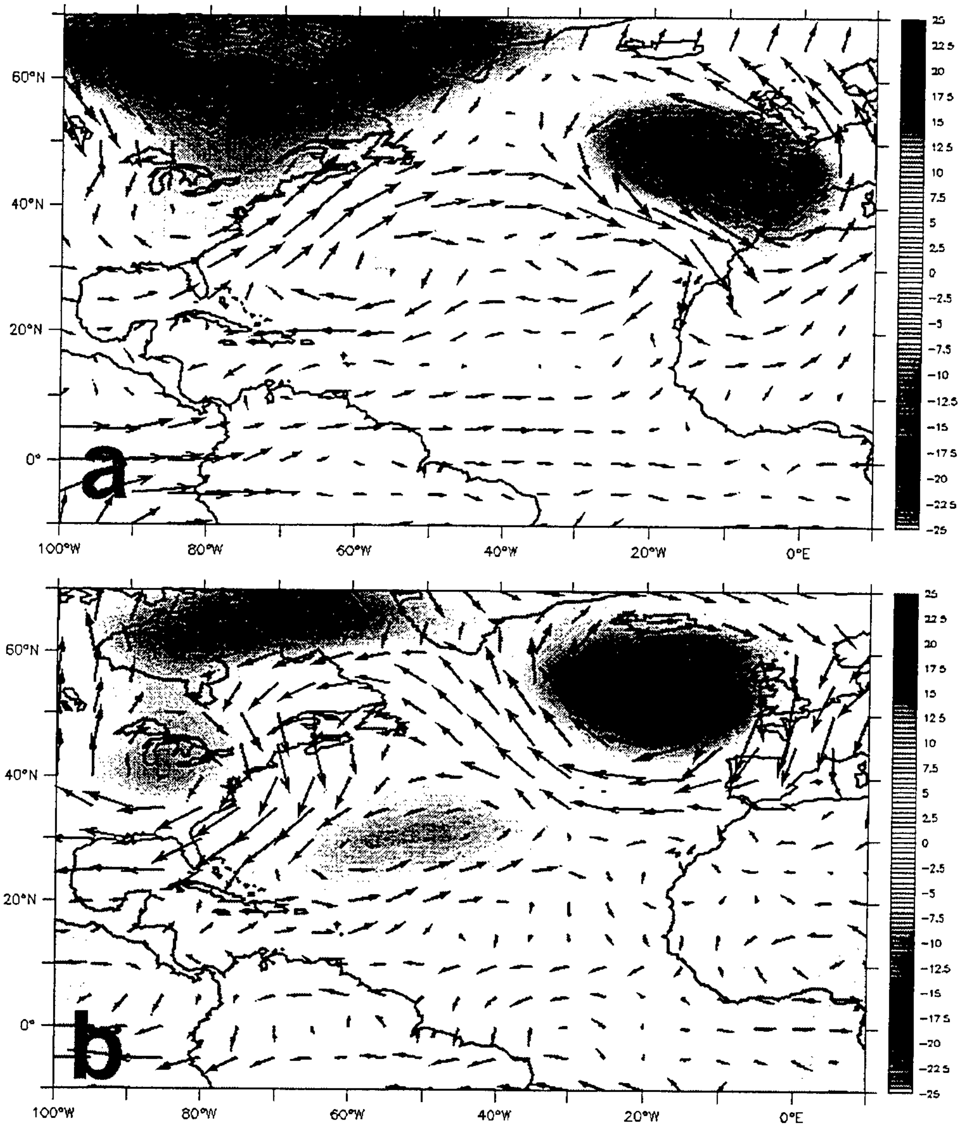

Figure 25. Anomalous 500 hPa geopotential heights and vector winds during SON. (a) El Niño; (b) La Niña. Note that during the EN (LN) events, there were anomalous westerlies (easterlies) flow over the Gulf of Mexico, and anomalous southwesterlies (northeasterlies) over and near the east coast of the U.S. A vector five degrees long represents a wind speed of approximately 5 m/s. Height anomaly color scale is to the right of figures.

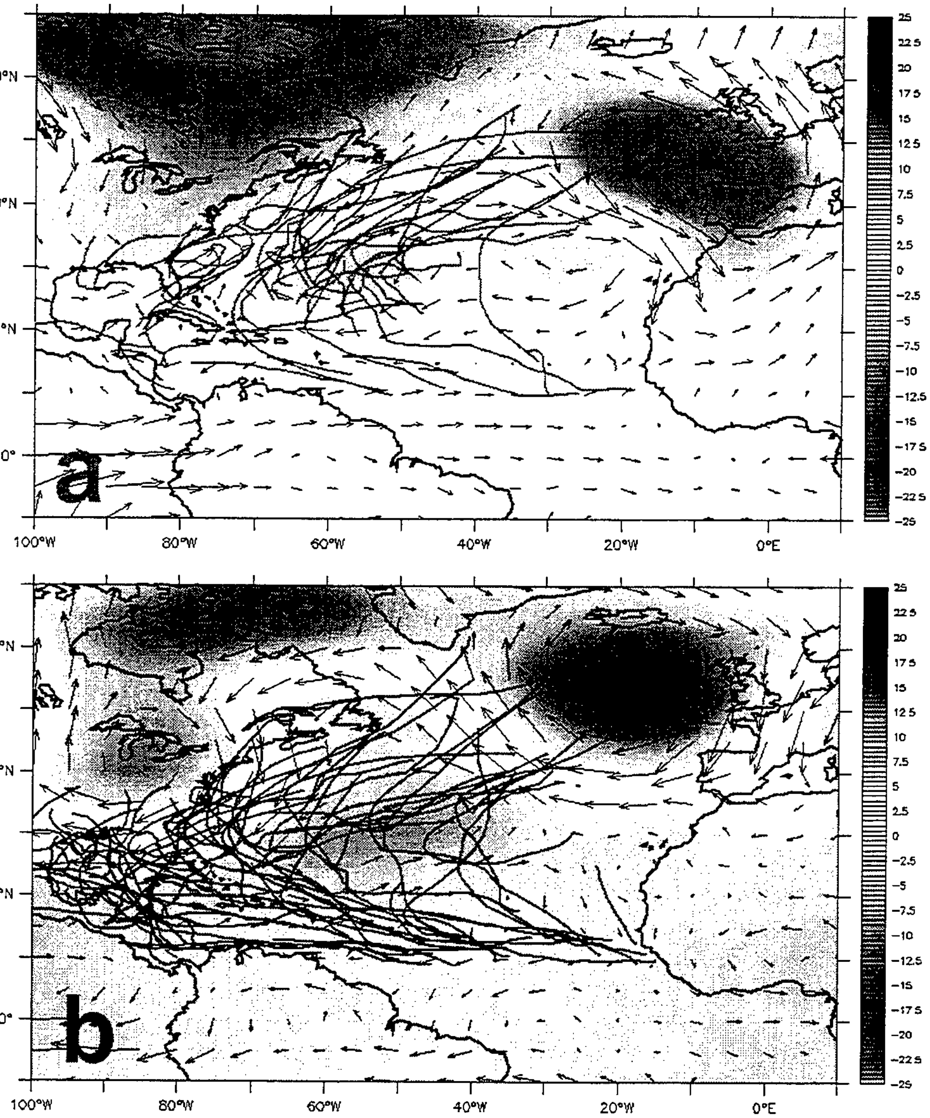

Figure 26. TC tracks and anomalous 500 hPa geopotential heights and winds during JAS. (a) El Niño; (b) La Niña. This figure contains the same information as Fig. 25, but with tracks added. The EN-LN differences in the tracks, and especially the differences in their proximity to U.S. coastal areas, is related to the differences in the steering flows implied by the anomalous 500 hPa winds (cf. Fig. 25). A vector five degrees long represents a wind speed of approximately 5 m/s. Height anomaly color scale is to the right of figures.

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